Light Level Analysis in Commercial Buildings

A Minnesota Market Study

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Executive Summary

Research in other Midwestern states has shown that Light-Emitting Diode (LED)-lit spaces in commercial buildings are often over-lit. This leads to excess energy usage and dissatisfied occupants. On behalf of Minnesota Department of Commerce, Division of Energy Resources, Slipstream collected information from Minnesota businesses on their light levels and associated lighting system characteristics. This information will help Minnesota Department of Commerce address savings opportunities from optimizing light levels through appropriate program offerings, educational strategies and resources.

The characterization study was comprised of both primary and secondary research. We reviewed studies germane to this project, conducted a segmentation of Minnesota lighting based on U.S. Energy Information Administration data, interviewed Minnesota energy efficiency program staff and a select group of stakeholders, and measured light levels in a representative sample of Minnesota businesses. We used the results from the site visits of Minnesota businesses and data gleaned from our literature review to quantify the potential for energy savings from optimizing light levels (often referred to as illuminance). We distilled lessons learned to clarify effective approaches for Conservation Improvement Program's (CIPs) to reach this market segment.

Lighting Segmentation in Minnesota

Commercial and manufacturing buildings in Minnesota use approximately 5.3 billion kWh of lighting energy annually. Five building types comprise approximately two-thirds of the lighting energy. Manufacturing (27%) and Education (12%) are the two largest market segments, with Warehouse (11%), Office (10%) and Outpatient Healthcare (6%) also comprising significant components.

Within the major building types, **the predominant and overlapping space types are open and private offices, conference rooms, warehouse areas, and corridors (including hallways and stairwells). We also included classrooms as they were of interest to the Minnesota Department of Commerce program staff.** Open plan offices are ideal for adjusting light levels since the light levels and electrical power of a significant amount of lighting power can be affected with one adjustment. This minimizes the time and associated cost of achieving savings. Other good candidates are space types with many similar spaces such as private offices and classrooms. In these situations, the amount of adjustment can be determined in one space and quickly applied to the other similar spaces. Our space types of interest comprise the majority of the area in each of the major building types.

LEDs are inherently dimmable, meaning their light output and corresponding lighting energy could easily be reduced in overlit spaces. LEDs are rapidly increasing their share of the new and replacement lighting market. The United States Department of Energy (DOE) estimates that in 2012, LEDs comprised only 1% of the market. However, this increased to 3% in 2014 and 12.6% in 2016.[1] The DOE further projects that by 2020, LEDs will comprise 48% of the lighting market.[2] Using this information, we estimated the

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[1] State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs, Version 3.0

[2] Navigant, "Adoption of Light-Emitting Diodes in Common Lighting Applications", July 2017.

portion of commercial spaces in Minnesota served by LEDs in 2020. **Across all the commercial building types of interest, LEDs serve 11.0% of the total area.**

Task tuning, or high-end trim, is the adjustment of electric light levels by limiting the maximum light output and power of lighting systems. This control allows for the adjustment of light levels in existing overlit spaces, thereby saving electrical energy. There is currently a low penetration of high-end trim of lighting systems in Minnesota buildings.

Site Visits

We visited a total of 36 buildings across Minnesota. Within these buildings, we quantified the mean illuminance for our sample by space type (Table 1).

Table 1: Mean, standard deviation, and relative precision average illuminance in footcandles (fc) by space type.

Space Type	Mean	Standard Deviation	Relative Precision at 95% Confidence Interval (CI)
Open Office	49.6	18.3	7.1
Private Office	47.7	17.7	5.0
Conference Room	45.2	17.9	6.0
Warehouse	31.2	21.1	8.4
Corridor	34.5	16.7	6.9

We then calculated the degree to which the mean illuminance differed from the Illuminating Engineering Society (IES) recommendation for each space type, expressed as the percent reduction needed to bring the mean into agreement with the recommendation (Table 2).

Table 2: Mean, IES recommendation, and percent reduction average illuminance (fc) by space type.

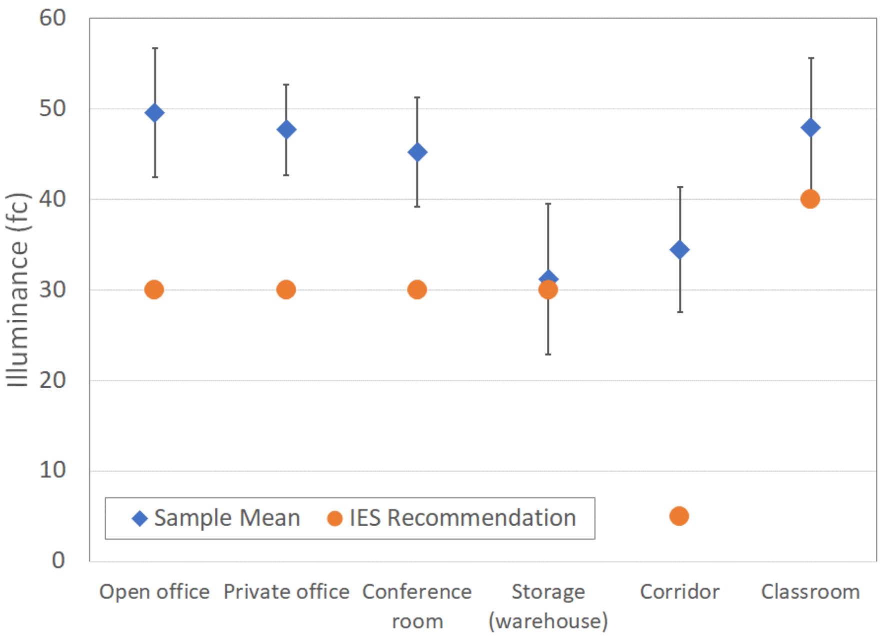
Space Type	Mean	IES Recommendation	% Reduction
Open Office	49.6	30	40%
Private Office	47.7	30	37%
Conference Room	45.2	30	34%

Space Type	Mean	IES Recommendation	% Reduction
Warehouse	31.2	30	4%
Corridor	34.5	5	86%
Classroom	48	40	17%

For all space types, the mean illuminance was higher than the IES recommendation. This means that energy savings could be captured by bringing the two into agreement. In Open Offices, Private Offices and Classrooms, this illuminance reduction potential was 40%, 37%, and 17%, respectively. This reduction potential is significant, considering the quantity of these space types in Minnesota. Conference rooms were also very overlit, needing a reduction of 34% to bring their mean illuminance into agreement with the IES recommendation. Corridor spaces were the most overlit (86%). There is less opportunity for aggregate energy savings in these spaces due to their smaller portion of overall building area. In addition, the IES recommendation of 5 fc for corridor spaces may be considered too aggressive of a reduction by facility staff and building occupants, thereby reducing the energy savings potential. Warehouse was the only space type with a mean illuminance essentially on par with the IES recommendation (4% reduction). This may be due to a higher focus by lighting designers to properly illuminate the racked aisles of warehouse spaces.

When the mean illuminance and IES recommendations are presented visually (Figure 1), the difference between the two is more striking.

Figure 1: Mean versus IES recommended illuminance.



Expected Savings Estimates

The final estimated achievable savings potential from light level adjustment incentive programs in Minnesota are shown in Table 3.

Table 3: Achievable potential savings from light level adjustment in Minnesota.

Building Type	Estimated electricity savings (MWh)	Annual dollar savings ($)	Avoided GHG emissions (tCO2 eq.)
Office	95,520	$10,354,346	86,827
Education	45,433	$4,924,901	41,298
Manufacturing	9,183	$995,481	8,348
Warehouse	16,805	$1,821,677	15,276
Total	***166,941***	***$18,096,405***	***151,749***

In total, we estimate that adjusting light levels could potentially save Minnesota approximately 167,000 megawatt hours (MWh) annually, with most of these savings coming from the Office and Education sector. This energy savings is equivalent to 15,500 typical Minnesota household's annual electric consumption,[3] reducing greenhouse gas emissions by approximately 152,000 tons of carbon dioxide equivalent (tCO2 eq), or the equivalent of taking 32,000 passenger vehicles off the road for a year.[4] This energy savings equates to over $18 million cost savings to Minnesota businesses. Note that this savings potential estimate assumes 88% of Minnesota lighting across these facilities is first upgraded to LEDs by 2035 and that 58% of these lights are easily tunable.[5] It also assumes a program achievability factor of 57.5%.[6]

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[3] Annual electricity consumption of typical Minnesota household of 10,766 kWh/yr. U.S. Energy Information Administration (2012). "Average monthly residential electricity consumption, prices, and bills by state." http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3

[4] Annual greenhouse gas emissions from passenger vehicles of 4.75 tCO2. U.S. Environmental Protection Agency (2011). "Greenhouse Gas Equivalencies Calculator." https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

[5] Navigant, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", December 2019.

[6] Minnesota Energy Efficiency Potential Study: 2020-2029. CARD Final Report, contract #121430. https://mn.gov/commerce/policy-data-reports/energy-data-reports/?id=17-361187

The Lighting Segmentation section contains more detail regarding the calculation approach for these estimates.

Cost Effectiveness

We estimated cost effectiveness under two scenarios: a new system associated with a new construction or major renovation project or an existing system. Using these scenarios, we calculated simple paybacks as outlined in Table 4.

Table 4: Cost savings and simple paybacks for task tuning LED systems.

Space Type	Cost Savings ($/ft^2)	Simple Payback (yr) New Construction	Simple Payback (yr) Existing
Office	$0.092	0.6	1.2
Conference	$0.086	0.6	1.3
Warehouse	$0.005	11.3	22.5
Corridor	$0.114	0.5	1.0
Classroom	$0.035	1.6	3.2

Except for Warehouse spaces, the cost savings and associated simple payback of task tuning LED systems are very good. For these cases, we calculate a cost savings of between $0.035 and $0.114 per square foot (ft^2), resulting in a simple payback of between 0.5 and 1.6 years (yr) for the new construction and between 1.0 and 3.2 years for existing system cases, respectively. For Warehouse spaces though, the lower lighting power density and light level reduction lead to long simple paybacks. **Due to these short payback periods, we recommend that task tuning be implemented in new construction projects or major renovations in which a dimming system is already planned as part of the design requirements. For the same reason, if a dimming system already exists in a facility, task tuning should be strongly considered to achieve cost-effective energy savings.**

Expedited Assessment

We investigated alternate approaches to estimating illuminance that would be quicker without unacceptably reducing accuracy. These expedited assessments included:

- Reduced Sampling Approach: measuring fewer points and/or using a simplified calculation method than the IES Lighting Handbook's procedure
- Photometric Analysis: estimating illuminance using computer models
- Occupant Satisfaction Correlation: using occupant surveys instead of measurements or models

We concluded that a Reduced Sampling Approach could save time without significantly sacrificing the overall accuracy of the calculated illuminance.

Overall, we found that Photometric Analysis does a good job of estimating light levels. Our models were on average within 4.4% of measured illuminance and ranged from 0.85% to 8.9%. We conclude that photometric analysis is a useful tool for evaluating illuminance values and identifying opportunities for task tuning and associated energy savings. Although models are less accurate than field measurements, the reduced time involved justifies the relatively small tradeoff in accuracy.

Unfortunately, there was insufficient data for correlating the occupant satisfaction surveys with how overlit a space was. However, the limited dataset suggests that better occupant survey scores correlate to light levels in better agreement with IES recommendations. Although occupant surveys alone are insufficient to assess the light levels in a building, they are an important tool for service providers. We recommend deploying them to the extent reasonable on lighting projects.

Occupant Comfort

Task tuning is essentially a tradeoff between energy consumption of a lighting system and light levels in a space. When performing task tuning, it is important to balance energy savings with occupant visual comfort, as tuning that is too aggressive may result in high energy savings at the expense of occupant satisfaction.

Complicating this balance is the fact that occupants perceive light levels differently both amongst individuals and under varying situations. Because of this complication, **we recommend that task tuning be conducted with occupant feedback in order to balance energy savings and occupant visual comfort.** Although this may result in lower immediate energy savings, it would increase energy savings persistence, as facility managers would be less likely to override tuned controls based on occupant complaints.

Reviewing Minnesota Programs

We interviewed Minnesota programs staff and a select group of stakeholders for their insights on lighting in Minnesota businesses.

Key takeaways from interviews with Minnesota utility, muni/coop, and program implementation program staff include:

- Lighting programs are largely driven by prescriptive rebates on LED light fixtures and linear LED tubes. Prescriptive rebates for controls are also offered in some areas but have much lower uptake. Downstream incentive strategies are more widely used than midstream approaches.
- One-for-one fixture replacements represent the largest share of current program participation, producing 60-90% of lighting program savings. Most retrofit projects involve installation of linear LED tubes, but the share of LED fixture installations is increasing.

- Most lighting projects involve retrofits of existing spaces. New construction projects are a smaller share of lighting projects, contributing 10-15% of lighting program savings. Lighting projects in tenant fit-outs are not common, though may be slightly more prevalent in urban/suburban areas (max 15% of lighting projects).
- Challenges cited by commercial lighting program managers include:
    - Concerns about future program impacts when savings from LED lighting decline over time due to more stringent code baselines and market saturation of LEDs.
    - Diversifying sources of energy savings beyond lighting.
    - Finding new ways to promote deeper customer engagement in energy efficiency programs.
    - Limited number of lighting design experts serving rural areas; contractors serving these areas are typically looking for fast wins and may be less willing to take on projects with more complexity.
- The building types that deliver the most lighting projects include office, manufacturing, retail and education.
- Most programs leverage trade allies to recruit and install projects, typically engaging with electrical contractors. Some interviewees cited challenges engaging lighting distributors.
- Program staff do not encounter significant barriers on LED retrofit projects. Paybacks are good and capital barriers may cause project delays but do not often prevent projects from being done if customers are interested. Lighting controls projects are more complex, less cost-effective, and have seen lower adoption to date.
- Measurement of light levels is not often done on lighting retrofit projects, and when it is done, it is more often done to ensure the light level is at least the same or more than what was produced by the lighting being replaced.
- Program staff were mixed about whether a program should play a role in assessing light levels. Some felt it was a “policing” function they do not want to perform. One utility noted it is a service they provide if customers ask for it.
- Most program staff thought light level optimization could be a viable future strategy if the economics are good from a customer and program standpoint.
- Light level optimization could also be a strategy for deeper customer engagement, but program managers noted the following challenges must be understood and addressed.
    - The customer decision process is different for lighting control projects than lighting retrofits, and there are more stakeholders involved.
    - Light level optimization involves a more complex set of occupant preferences, particularly when people in the same space have different preferences.
    - Lighting systems with advanced controls are more costly and take more time to commission, particularly when occupant feedback is considered and addressed.

  - Marketing light level optimization to customers who have completed a recent lighting retrofit must employ careful messaging. Need to avoid the implication that the customer is getting less value from the original LED retrofit than expected.

Our interviews with program stakeholders included manufacturers, energy efficiency consultants, electrical contractors and lighting sales representatives. Key takeaways include:

- The major lighting manufacturers have LED products with task tuning capabilities. As compared to code-required controls, the incremental cost of lighting fixtures capable of dimming is small to none.
- Contractors' lack of familiarity with programming requirements of advanced wireless systems often leads to costs one- to two-times more expensive than a basic low-voltage wired system. As contractor familiarity with these systems increases and manufacturers continue making them more plug-and-play, these costs will continue to decrease.
- In order to support light level optimization, designers need to understand which control products have dimming and high end trim capabilities and include these capabilities in their design specifications.
- There is a general sense that customers are reluctant to install lighting controls (except where code-required) because they do not understand all the benefits.
- Most stakeholders interviewed indicated most of their lighting projects are one-to-one fixture replacements in existing spaces, but they are seeing increasing interest in going further. Smaller lighting retrofit projects tended to be one-to-one fixture replacement with little interest beyond code compliance.
- Generally, the stakeholders we interviewed see over-lighting as an issue. They generally indicated that the conversion to LED lighting fixtures creates over-lit spaces that could be task tuned to 75-80% of the designed light level.
- At the same time, light levels are subjective; individuals have different brightness preferences. The more volumetric nature of LED lights as compared to the fixtures they are replacing also plays into this perception of brightness. So, getting occupant feedback on light levels is more important than simply taking light meter measurements.
- Besides capital cost, the following other barriers were identified for implementing systems capable of task tuning:
  - More complex systems to install, commission and operate
  - Contractor and end user awareness. It takes significant time to educate someone on the benefits of controls. However, once they understand the system, they often will begin implementing the system on their projects. This is easiest with larger building or portfolio owners.
  - Varied personal preference for light levels
  - Security concerns related to connecting a potentially unsecured system to the building's network.

- A few of the interviewees consider light levels in about 75% of their projects. They indicated that they set minimum illuminance targets to code or requirements established by the Illuminating Engineering Society (IES). They use photometric calculations to hit the target and to advise their clients on the possibility of reducing fixture count while maintaining or improving lighting performance. However, photometric calculations are often done with little to no knowledge of the furniture and finishes used in the space. There is little to no follow-up measurement of light levels in these spaces once lighting is installed.
- Other metrics these companies use include: illuminance uniformity ratios; evaluation of contrasts and shielding of light sources to reduce glare; color rendering index; and WELL Building standards.
- Most of these companies are aware of utility programs in Minnesota that provide incentives for energy efficient lighting. They would like to see these programs do more to encourage advanced controls and light level optimization, including revisiting previous retrofit projects to further optimize light levels. Other suggestions included:
    - Provide rebates for distributed digital controls (rather than just occupancy or photosensors sensors)
    - Provide rebates for manual dimmers
    - Move away from fixture-based incentives
    - Develop upstream programs that allow for manufacturers and distributors to pass along rebates to customers. These organizations have the information (bill of materials, invoices) required for the application. This, combined with economies of scale, allow for easier and more efficient interaction with the program.
    - Once established, keep a program similar over time
    - Determine a set of required contractor certifications for program participation
    - Collaborate more with lighting designers on determining appropriate light levels

Program Strategies to Optimize Light Levels

There is growing potential in Minnesota to capture energy savings from lighting control strategies like task tuning. LEDs are gaining market share for a range of interior applications. Even when dimmable lighting systems are installed, task tuning the system is not standard practice and many spaces are over-lit as a result.

A range of energy efficiency program strategies can be deployed to promote optimized light levels in commercial buildings, from enhancements to existing prescriptive lighting programs to new stand-alone initiatives (Table 5).

Table 5: Program approaches for advanced lighting controls

Strategy	Description	Incentive Approaches
Prescriptive lighting program enhancements	Higher incentives for dimmable fixtures	$/unit
	De-lamping incentives	$/unit
	Incentive bonus for including task tuning in the lighting retrofit project scope	$\$/\text{ft}^2$
Task tuning of previously-installed dimmable LED lighting	Incorporate measurement of light levels and task tuning into retrocommissioning (RCx) program scope	$/kWh
	Stand-alone initiative to revisit buildings that have installed dimmable LEDs + controls; measure light levels and tune to IES recommendations	$\$/\text{ft}^2$
Advanced lighting incentives	Incentives for installation of Networked Lighting Controls (NLC), luminaire-level lighting controls (LLLC), design assistance, commissioning	$\$/\text{ft}^2$ $/unit $/kWh

Prescriptive lighting programs are prevalent and there is plenty of opportunity for deploying strategies that promote optimization of light levels. Offering incentives for delamping can motivate needed reductions in the number of installed tubular (or troffer) LEDs (*TLEDs*) in a lighting retrofit. Programs can also provide guidance to help customers select the right lumen package when they purchase non-dimmable fixtures. Best practice is to use photometric modeling to identify the lumen package for a fixture selection that provides the recommended illuminance for a given space. Several manufacturers provide controls hardware that can be layered onto existing dimmable LEDs to enable more advanced control strategies like task tuning, and these products can be incentivized. Prescriptive programs can offer incentive bonuses for customers that install dimmable fixtures and demonstrate that task tuning has been completed. They can educate trade allies about the benefits of task tuning and provide training on the procedures involved. Task tuning can also be implemented as a separate stand-alone program serving sites that have already been retrofitted to LED fixtures with appropriate controls, though it is most cost-effective to optimize light levels at the time of the lighting retrofit.

Retrofit programs pursuing task tuning opportunities should target the following:

- Building size minimum of 25,000 square feet
- High opportunity building type such as office, education or manufacturing
- LED fixture retrofit done in the last 3 years
- Installed dimmable fixtures and controls capable of deploying high end trim

Typical electricity and peak demand savings from implementing task tuning are shown in Table 4. Offices represent the highest opportunity building type and warehouses represent the lowest.

Table 6: Typical electricity and peak demand savings.

Building Type	Typical Electricity Savings (kWh/ft^2)	Typical Peak Demand Savings (W/ft^2)
Office	1.03	0.23
Education	0.46	0.13
Manufacturing	0.14	0.03
Warehouse	0.17	0.04

A targeted program to implement task tuning of existing lighting in commercial buildings would most likely involve training electrical contractors in a protocol of measuring light levels similar to the approach described in the *Expedited Assessment* section of this report, as well as the steps for adjusting light levels to the recommended values. The training would ideally also include strategies for occupant engagement and education. Existing training resources from IES and the Lighting Controls Association can be leveraged.

Task tuning is essentially a tradeoff between energy consumption of a lighting system and light levels in a space. When performing task tuning, it is important to balance energy savings with occupant visual comfort, as aggressive tuning will result in high energy savings at the expense of occupant satisfaction. Helping building occupants understand the value of light level optimization and soliciting their input in the process will most likely help with savings persistence.

Serving larger buildings increases the viability and cost-effectiveness of task tuning programs. Programs can employ targeting strategies to boost cost-effectiveness. The most cost-effective task tuning projects involve buildings with large areas of similarly controlled lighting, such as large open offices or a number of classrooms for which the same level of tuning could quickly be applied. Regardless of the building, it is likely not cost-effective to measure the light levels in all spaces. Rather, a sample of representative spaces should be identified and measured. The resulting lighting level reduction can then be applied to all similar spaces. Additionally, networked lighting systems that come with an online programming interface can be tuned quickly, even allowing tuning to occur through a simple programming interface after measurement occurs. Task tuning is more time-consuming in non-networked systems because the changes must be made on-site via adjustments at each control device. It is also more cost-effective to deploy task tuning at the time of the lighting retrofit instead of coming back to implement task tuning on a subsequent visit. There is a high fixed cost in merely getting into the building, understanding the space types and associated lighting controls. If task tuning is part of the retrofit process, the time associated with actually tuning the lights is relatively short.

Introduction

On behalf of the Minnesota Department of Commerce, Division of Energy Resources, through the Conservation Applied Research and Development (CARD) program, Slipstream collected information from Minnesota businesses on their light levels and associated lighting system characteristics. This information will help utility CIPs address savings opportunities from optimizing light levels by identifying appropriate program offerings and resources.

Background

Lighting in commercial buildings has been the target of energy efficiency programs for years, with the primary strategy being one-for-one fixture replacement. However, recent changes to federal standards for fluorescent lamps and more stringent building and product codes, have begun to erode these program savings. Market changes are forcing energy efficiency programs to look beyond efficacy-based, per- product incentives. Research suggests that significant savings potential exists through task tuning of light levels and redesign of overlit spaces. However, the average light level (often called illuminance) in typical spaces in Minnesota, as well as associated lighting system characteristics, is not well understood. A light level characterization, including site visits to accurately measure light levels, will fill this knowledge gap and lead to opportunities for increased energy savings. Slipstream designed and conducted this research study to provide Minnesota utilities with data that will help push customers to implement more comprehensive lighting upgrades that could include controls, lower wattage fixtures, and task tuning.

Methodology

The market study was comprised of both primary and secondary research. We reviewed studies germane to this project (summarized in Appendix A: Literature Review), conducted a segmentation of Minnesota lighting, interviewed Minnesota utility energy efficiency program staff and a select group of stakeholders, and visited a sample of Minnesota businesses. We used the results from the site visits of Minnesota businesses and data gleaned from our literature review to quantify the potential for energy savings from optimizing light levels. We distilled lessons learned to clarify effective approaches for CIP programs to reach this market segment.

Lighting Segmentation

The goal of the segmentation is to better understand indoor lighting in Minnesota commercial buildings. This segmentation provides clarity and direction to the remainder of the project, as well as quantifies the lighting energy and relevant characteristics for programmatic planning. The U.S. Energy Information Administration's (EIA) Commercial Building Energy Consumption Survey (CBECS) microdata includes characteristics about lighting types, lighting controls and the buildings they serve. The EIA's Manufacturing Energy Consumption Survey contains supplementary information about the lighting in manufacturing facilities. In order to make this preliminary analysis specific to Minnesota, we aggregated the data within Minnesota's census division, West North Central, which also includes Iowa, Missouri, North Dakota, South Dakota, Nebraska and Kansas. To understand Minnesota's portion of this region's lighting, we used population prorating using U.S. Census data. Specifically, we prorated the census division's lighting energy by 26%. Finally, the latest CBECS survey was completed in 2012. To understand the scale of lighting in 2020, we assumed a 2% growth rate in agreement with EIA data for the growth of commercial building area and that 6.7% of the applicable existing lighting was retrofit each year per the Minnesota TRMs assumption of 15 years for T8 fixture life. We further used DOE estimates for the penetration of LEDs. [7]

Minnesota Program Interviews

Energy efficiency programs have captured a large amount of energy savings from LED retrofits in recent years, with the primary strategy being one-for-one fixture replacement in commercial buildings. However, changes to federal standards for fluorescent lamps, more stringent codes, and the increasing prevalence of LED technology are changing program baselines and reducing future savings potential. Market changes are forcing energy efficiency programs to look beyond efficacy-based, per-product incentives. Research suggests that significant savings potential exists through task tuning of light levels and redesign of overlit spaces.

We identified utility staff and program implementers working on commercial lighting programs in Minnesota. Through in-depth interviews, we examined current program offerings, staff perception of

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[7] Navigant, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", December 2019.

program needs, and vision for the future. The results of these interviews helped us tailor our research and recommendations to be most relevant and useful for Minnesota CIP programs.

Stakeholder Interviews

Lighting manufacturers, distributors and sales representatives, electrical contractors and energy efficiency service providers are key partners that ensure the success of commercial lighting programs in Minnesota. Their input is critical to informing the development of future program strategies that seek to promote task tuning of light levels and redesign of overlit spaces. Through in-depth interviews, we identified how these program allies currently make decisions, the extent to which they currently address light levels in their projects, and how a lighting optimization program offering would ideally be structured to achieve greatest market impact. The results of these interviews helped us tailor the project scope and recommendations to be most impactful on future CIP initiatives for commercial lighting.

We interviewed staff from ten businesses with varying roles in lighting projects in the Midwest. These businesses included lighting and lighting controls manufacturers, an energy efficiency consultant, an electrical contractor offering lighting retrofit design services with an emphasis on energy efficiency, manufacturer sales representatives offering some level of design services and distributors also offering some level of design services.

Site Visits

The main objective of this project was to quantify the light levels in commercial building spaces across Minnesota. We accomplished this by collecting a representative sample of average illuminance through on-site measurement in the most prominent space and building types. The information gathered in these site visits was later used to estimate the energy savings potential for adjusting light levels

Sampling Plan

The site-visit sample was drawn from the results of a short online screening survey (Appendix B: Screening Survey). The screening survey was implemented via phone calls to a random sample of Minnesota business contacts within geographically similar regions from an Infogroup database. The statistical inference from our study was limited to the scope of this database and the method used to collect the data.

The screening survey gathered information pertaining to each respondent's building characteristics. Specifically, the following high-level information was gathered:

- Building location
- Building type
- Building area
- Number of businesses in the building
- Primary lighting type

Note that the screening survey focused on four building types comprising approximately 60%[8] of Minnesota commercial and manufacturing building lighting energy; office, education, warehouse, and manufacturing. We filtered out buildings not associated with one of these building types.

We also filtered out buildings that did not have a significant portion of LED lit spaces.

We compared the geographic distribution of our random sample to ensure it is in relative agreement with Minnesota's commercial building population distribution. We used the latest commercial building census data for the comparison.[9]

The predominant and overlapping space types of our building types are open and private offices, conference rooms, and corridors. In warehouse and manufacturing buildings, we additionally gathered data on warehouse spaces. In education facilities, we additionally gathered data on classroom spaces.

In order to determine a sample size, we assumed a mean average illuminance 20% above the IES recommendations for each space type.[10] We additionally assumed a standard deviation of 38% of the mean average illuminance based on measurements from a similar study in Wisconsin.[11] Sample size was then estimated by:

$$n = \left(\frac{Z \cdot \sigma}{RP \cdot \hat{x}}\right)^2$$

Where:

n is the sample size,

Z is the z statistic,

σ is the standard deviation

RP is the relative precision, and

$\hat{x}$ is the sample mean.

Using the stated assumptions, we estimated a sample size of 40 unique spaces for each space type was the minimum sample needed. Typically, some spaces are dropped from the final analysis for a variety of reasons, such as data corruption or facility staff changing their mind about participation. Therefore, we increased the sample by 10% percent to 44 to account for attrition.

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[8] From analysis of 2012 U.S. Commercial Building Energy Consumption Survey microdata and 2017 Manufacturing Energy Consumption survey data

[9] U.S. Census Bureau, 2014 ZIP Code Business Patterns. https://www.census.gov/newsroom/press-releases/2016/cb16-tps102.html

[10] DiLaura et al., The Lighting Handbook, Tenth Edition, 2011.

[11] Schuetter, et al., "Light Level Analysis in Buildings: A Market Characterization Study," prepared for Focus on Energy Environmental & Economic Research and Development Program, October 2018.

Table 7 summarizes each space type's assumed mean average illuminance, standard deviation, and relative precision, as well as the resulting target sample. The assumed mean average illuminance was 36 foot candles (fc) (with 13.8 fc standard deviation) for space types open office, private office, conference room, and warehouse. It was 6 fc (with 2.3 fc standard deviation) for corridors and 48 fc (with 18.4 fc standard deviation) for classrooms. The relative precision was 3.6 fc for space types open office, private office, conference room, and warehouse. It was 0.6 fc for corridors and 4.8 fc for classrooms. The target sample was 44 spaces for each space type.

Table 7: Assumed mean average, standard deviation and relative precision of illuminance and target sample by space type.

Space Type	Mean Average Illuminance (fc)	Standard Deviation (fc)	Relative Precision at 90% CI (fc)	Target Sample
Open Office	36	13.8	3.6	44
Private Office	36	13.8	3.6	44
Conference Room	36	13.8	3.6	44
Corridor	6	2.3	0.6	44
Warehouse	36	13.8	3.6	44
Classroom	48	18.4	4.8	44

Note that the common relative precision target of 10% at a 90% confidence interval is used. We assumed that we would find an average of one unique space of each space type at each building we visited. We further assumed that we would find an average of 2.25 warehouse spaces for each Warehouse and Manufacturing facility and 3 classrooms per Education facility. Given these assumptions, Table 8 summarizes our building type targets. We had a target of 10 buildings for each of the office, warehouse, and manufacturing building types and a target of 15 education buildings for a total of 45 sites.

Table 8: Building type targets

Building Type	Recruitment Target
Office	10
Education	15

Building Type	**Recruitment Target**
Warehouse	10
Manufacturing	10
Total	***45***

Our 45 proposed site visits and assumed unique spaces per site would presumably allow us to reach our target number of unique space types and confidence interval targets. Note that we define a unique space as one that has a unique light level due to a unique lighting layout or fixture type. The assumption underlying this definition is that it would not improve statistical significance to include very similar spaces in our sample (i.e., identical private offices). The space types of interest are common to all major building types, so it was likely that we would find at least one of each in each building. However, in many buildings, such as multi-tenant buildings, buildings with additions or buildings with varying lighting approaches, we found many more unique spaces.

Once identified, the site-visit sample was recruited through follow-up phone calls.

Site Visit Protocol

For this sample of spaces, we used a protocol we developed for previous research we've conducted on lighting levels in businesses to collect information on uniformity, lighting parameters, control parameters, geometry, and architectural properties for each space. We followed IES's procedure for carefully selecting measurement locations to calculate average illuminance and determine the approximate maximum and minimum values of each space.[10] This data allows us to quantify both the light level and uniformity relative to IES recommendations. Data was collected using a tablet-based form as outlined in Appendix C: Site Visit Protocol.

Occupant Survey

After we conducted a site visit, we followed-up with an online occupant survey. This survey was designed to gauge the occupant's level of satisfaction with their light levels, visual comfort and controllability of the lighting in their space. This data allows us to correlate measured light levels with occupant satisfaction. Data was collected using an online form as outlined in Appendix D: Occupant Survey.

Analysis

Our data analysis began by ensuring data accuracy. Data accuracy assures that results are admissible for CIP program design, calculations, and evaluation. Our first level of quality control involved training our field technicians to ensure they gathered quality data. This training included the following steps:

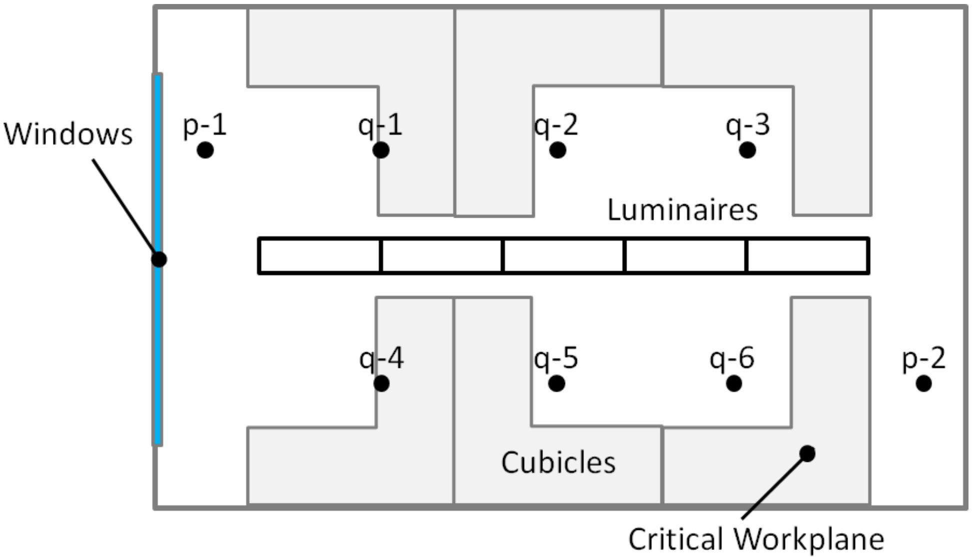
- Lighting basics including different lighting types, fixture types and control options.
- IES light level measurement approach including identifying the applicable luminaire configuration and light level measurement locations.
- Proper light level measurement technique. This included waiting for the lighting system to warm up such that the light it provided was at steady state, as well as minimizing the researcher's effect on the reading by utilizing a tripod and standing back from the light meter. We further minimized the effect of daylight on our readings by closing any blinds and taking readings with the lights on followed immediately by readings with the lights off. The difference in these two readings was used to calculate the electric light component of the measured illuminance.
- Practice site visits with all field technicians to ensure consistent measurements techniques across the team. These preliminary site visits identified gaps in our protocol and pointed to ways of improving data gathering accuracy.

The use of the tripod also allowed for consistent, horizontal readings at the workplane. We further ensured that the Extech EV31 light meter was calibrated traceable to National Institute of Standard and Technologies. Once data was in hand, our quality control checks for data accuracy included high level tabulations to identify and address:

- Significant gaps in data
- Data outliers that exceed reasonable limits of minimum and maximum measured illuminance

Once a quality data set was established, we used the measured illuminance data to calculate the average illuminance of each space. One method for calculating average illuminance is to take readings on a 2' × 2' grid throughout the entire space and then average the measurements. However, this method is time-intensive, requiring many readings for even relatively small spaces. We therefore followed the IES Lighting Handbook's procedure for calculating average illuminance.[10] This procedure is more focused, defining key positions for illuminance readings based on a given lighting system's luminaire configuration type. Figure 2 shows one luminaire configuration type: Regular Area with Single Row of Continuous Luminaires. This example diagram shows an office space with a window and cubicles, with a row of continuous luminaires running horizontally through the center of the room. There are nine total measurement points shown in the diagram, two of which are measurement points taken in the corners (p-1 and p-2). There is a critical workplane measurement point, and the other measurement points are evenly disbursed on either side of the row of luminaires (q-1 through q-6).

Figure 2: Light meter measurement points for regular area with single row of continuous luminaires.



Note that the measurement points (i.e. p-1, p-2, q-1…) are specific to the luminaire configuration type, and the number of total points is greatly reduced when compared to a regular 2’ × 2’ grid. The average illuminance, E_{ave}, for this specific luminaire configuration is given by:

$$E_{ave} = \frac{Q(N_{lum} - 1) + P}{N}$$

Where:

E_{ave} is the average illuminance in a given space in fc,

N_{lum} is the number of luminaires in the space,

Q is the average of the illuminance measurements taken at the q-labeled points in fc, and

P is the average of the illuminance measurements taken at the p-labeled points in fc.

Other luminaire configurations have different key measurement points and different equations for finding the average illuminance.

We further calculated each space’s lighting power, lighting power density and percentage of lighting power controlled by occupancy and photosensors. The lighting power for each space was calculated by:

$$P_{tot} = \sum_{i=1}^{n_{fixtype}} \sum_{j=1}^{m_{fix}} P_{i,j}$$

Where:

$Ptot$ is the lighting power of a given space in W,

$P_{i,j}$ is the fixture power of fixture type *i* and fixture *j* in W,

$n_{fixtype}$ is the number of fixture types in a given space, and

m_{fix} is the number of fixtures of a given fixture type in a given space.

The lighting power density for each space was calculated by:

$$LPD = \frac{P_{tot}}{A}$$

Where:

LPD is the lighting power density of a given space in W/ft^2,

A is the area of a given space in ft^2.

The percentage of lighting power controlled by occupancy sensors was calculated by:

$$\%_{occ} = \frac{\sum_{i=1}^{n_{fixtype}} \sum_{j=1}^{m_{fix}} \left(P_{i,j} * \%_{occ,i,j}\right)}{P_{tot}}$$

Where:

$\%_{occ}$ is the percentage of lighting power that is occupancy-controlled in a given space, and

$\%_{occ,i,j}$ is the percentage of fixture type *i* and fixture *j* that is occupancy-controlled in a given space.

The percentage of lighting power controlled by photosensors was calculated by:

$$\%_{photo} = \frac{\sum_{i=1}^{n_{fixtype}} \sum_{j=1}^{m_{fix}} \left(P_{i,j} * \%_{photo,i,j}\right)}{P_{tot}}$$

Where:

$\%_{photo}$ is the percentage of lighting power that is photocontrolled in a given space, and

$\%_{photo,i,j}$ is the percentage of fixture type *i* and fixture *j* that is photocontrolled in a given space.

We performed a quality check on these estimates and either corrected issues that were identified or developed reasonable explanations for them. These quality checks included:

- Average illuminance deviation from IES recommendations
- Lighting power density deviation from code requirements
- Aggregate occupancy and photosensor controlled percentages compared to typical market penetration rates as summarized in the Lighting Segmentation results section.

Overall mean illuminance for each space type was calculated as:

$$E_{mean} = \frac{\sum_{k=1}^{n_{spaces}} E_{ave,k}}{n_{spaces}}$$

Where:

E_{mean} is the mean illuminance for a given space type in fc, and

n_{spaces} is the number of spaces for a given space type,

Once we determined the mean illuminances, we calculated the percentage that a given space type's light levels could be reduced to bring it in agreement with IES recommendations:

$$\%_{reduction} = \frac{E_{mean} - E_{recommended}}{E_{recommended}}$$

Where:

$\%_{reduction}$ is the percentage reduction of a given space type,

$E_{recommended}$ is the IESIES illuminance recommendation for a given space type in fc, and

E_{mean} is the mean average illuminance for a given space type in fc.

In order to quantify Minnesota's statewide potential for energy savings from task tuning we extended the findings from our study to the population of studied commercial buildings within the state. We used data from CBECS, the U.S. Census and our measured results, to understand lighting energy use and potential savings from task tuning for the four building types studied as part of this project; Office, Education, Warehouse and Manufacturing. From our segmentation, we had previously quantified the total amount of lighting energy attributable to each building type in Minnesota, the percentage that could be tuned, as well as the percentage of each building type's floor area (and therefore lighting energy) from each of our space types.

We assumed that a program would bring the measured mean average illuminance into agreement with the IES recommended illuminance for each of the space types, capturing a proportionate amount of energy savings. Note that we used the LED-lit space illuminance results when establishing the percent to which the light levels could be reduced by. We applied these savings to the lighting energy consumption, scaled to our buildings types via the space breakouts discussed in the Lighting Segmentation section. This calculation represented the technical potential of lighting energy savings from task tuning. We finally assumed an achievability factor of 57.5%, meaning utility CIP programs could capture only this portion of the technical potential.[12] Note that these estimates are conservative as savings could additionally be captured from other building sectors.

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[12] Center for Energy and Environment et al., "Minnesota Energy Efficiency Potential Study: 2020-2029", prepared for the Minnesota Department of Commerce, Division of Energy Resources, December 2018.

Achievable electricity savings was converted to dollar savings using an average electric utility rate of $0.1028/kWh.[13] We used conversions outlined in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 105-2014 to estimate greenhouse gas emissions saved in metric tons CO_2 equivalent.[14]

Expedited Assessment

Although the IES Lighting Handbook's procedure for calculating average illuminance is simpler that taking measurements on a 2' x 2' grid, it is still fairly time intensive and might not be practical for building managers, contractors or program field staff to implement. We therefore investigated alternate approaches to estimating illuminance that would be quicker without unacceptably reducing accuracy. These expedited assessments included:

- Reduced Sampling Approach: measuring fewer points and/or using a simplified calculation method than the IES Lighting Handbook's procedure
- Photometric Analysis: estimating illuminance using computer models
- Occupant Satisfaction Correlation: using occupant surveys instead of measurements or models

Reduced Sampling Approach

The IES methodology for calculating illuminance in a space involves measuring many points and entering them into a relatively complicated equation. We envisioned alternate methods that either used fewer measurements, simplified equations, or a combination of the two. Using the data collected from this field study, we simulated three reduced sampling approaches. To assess each approach's accuracy, we calculated the mean percent deviation between the reduced sampling and IES procedure illuminance estimates for each space. We then estimated mean percent deviation for each reduced sampling approach for each of the six luminaire configurations with 95% boot strapped confidence intervals. The three reduced sampling approaches are described below.

Method 1: Calculate the mean measured illuminance for all the sampling points. This simplification avoids using the IES procedure's custom formulas for each luminaire configuration and additional data associated with each (i.e. number of fixtures, number of rows of fixtures and/or room dimensions).

Method 2: Calculate the mean measured illuminance, but only measure one for each point type. This simplification avoids using the IES procedure's custom formulas and measuring multiple points within each point type (i.e. only 1 Q and 1 P point in Figure 2).

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[13] U.S. Energy Information Administration, Electric Power Monthly, January 2020, Table 5.6.A. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

[14] American Society of Heating, Refrigeration and Air Conditioning Engineers. "Standard 105-2014, Standard Methods of Determining, Expressing and Comparing Building Energy Performance and Greenhouse Gas Emissions", Table J2-D, pg. 23.

Method 3: Use the IES procedure's custom formulas, but only measure one point for each point type. This was like Method 2, but illuminance was calculated using IES procedure's custom formulas. These formulas often include additional data on the room such as number of fixtures, number of fixture rows, or room dimensions as previously described.

To assess how the results of our study might change if different sampling approaches were used, we simulated the estimation of mean illuminance for each space type using each of the three methods and compared the results to what was actually measured as well as the IES recommended light level for each space type. When simulating results from Methods 2 and 3, where only one point of each type was sampled, we sampled a random selection for each space sampled with a single iteration.

All simulations and analyses for investigating reduced sampling approaches were completed using a combination of custom scripts and existing tools in R, Version 3.6.3.[15]

Photometric Analysis

Photometric analysis involves using computer modeling to estimate illuminance in spaces. This modeling is a common part of lighting design. It is quicker than field measurements since it does not involve lengthy site visits. And since it is already a part of many projects, service providers could rapidly deploy it for quick determination of light levels and corresponding task tuning setpoints. We wanted to understand the accuracy of photometric modeling in predicting light levels. We therefore developed photometric models and compared their illuminance predictions to our field measurements on a subset of 10 spaces.

We used AGi32 to complete photometric analysis for open office, private office, classroom, and warehouse space types. The analysis evaluated spaces with and without partitions or racking and spaces retrofit with both integrated LED fixtures and LED tubular lamps.

Our photometric analysis followed the same process typical for lighting design needed to evaluate light levels, lighting uniformity and to aid in selection of luminaires. The modeling steps include creating room geometry, confirming appropriate surface reflectance (if available), locating and downloading IES files for all luminaires from the manufacturer's website, defining the fixtures within AGi32 and locating the newly defined fixtures within the geometry. We paid close attention to fixture spacing, mounting height, and aiming of luminaires.

The model results were then compiled and compared to the measured illuminance levels. We also developed suggestions for modeling techniques that led to the highest accuracy.

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[15] R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Occupant Satisfaction Correlation

Measurements and modeling give quantitative illuminance levels. However, the goal of a lighting design is to satisfy the visual needs of the occupants, which may vary from IES recommendations. Occupant surveys assess occupant satisfaction with pre-retrofit or post-retrofit illuminance, which serve as a proxy for their visual needs. We set out to understand whether satisfied occupants led to light levels that were higher than, lower than, or in agreement with IES recommended levels. We therefore correlated the results of our occupant satisfaction surveys with the degree to which a space was overlit compared to IES recommendations.

Results

The results from this study are presented as follows: first we describe the characteristics of installed lighting in Minnesota. We then present a summary of the primary data collected from the site visits. We illustrate the results of the different expedited approaches for determining light levels. We conclude with a summary of interview findings from energy efficiency program staff and lighting stakeholders in Minnesota. These results lead to our recommendations for program design and a discussion of the barriers that need to be overcome to make a program successful.

Lighting Segmentation

Market Segments

Commercial and manufacturing buildings in Minnesota use approximately 5.3 billion kWh of lighting energy annually. Five building types comprise approximately two-thirds of the lighting energy (Figure 3).

Figure 3: Lighting energy in commercial buildings in Minnesota

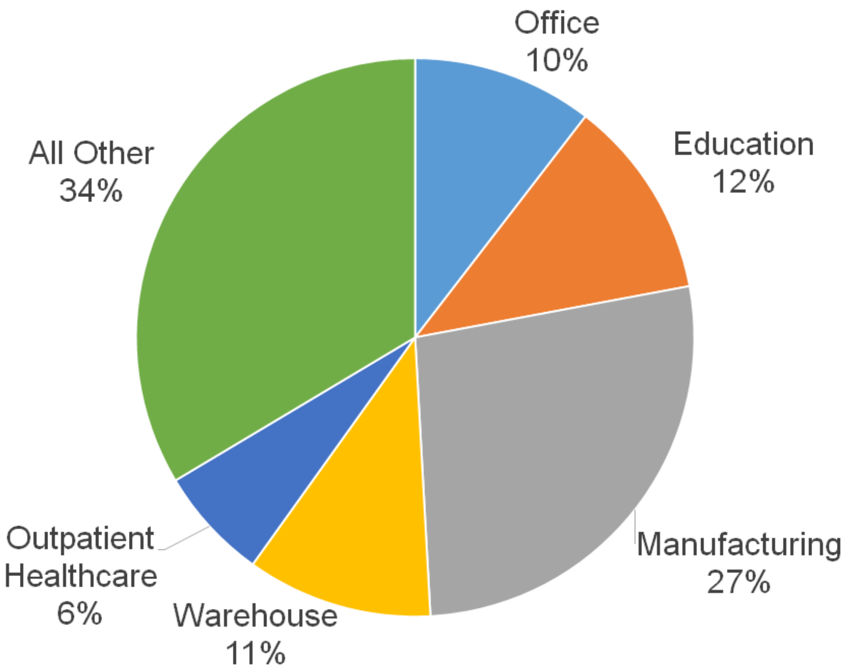

Figure 3 shows that manufacturing (27%) is the largest segment. Of the commercial buildings, Education (12%), Warehouse (11%) and Office (10%) are the largest market segments. Outpatient Healthcare (6%) also comprises a significant component of lighting energy but was not pursued within this study due to the perceived barrier of adjusting light levels in the healthcare sector. All other building types make up 34% of the lighting energy.

Space Types

Within the major building types, the predominant and overlapping space types are open and private offices, conference rooms, warehouse storage, and corridors. Open plan offices are ideal for adjusting light levels since the light levels and electrical power of a significant amount of lighting power can be affected with one adjustment. This minimizes the time and associated cost of achieving savings. CBECS data indicates that 34% of Office buildings have open plan offices. Other good candidates are space types with many similar spaces such as private offices and classrooms. In these situations, the amount of adjustment can be determined in one space and quickly applied to the other similar spaces. Using building energy modeling prototypes, we can estimate the approximate proportion of each building type comprised by these space types (Figure 4).[16,17]

Figure 4: Proportion of area for significant space types in commercial buildings in Minnesota

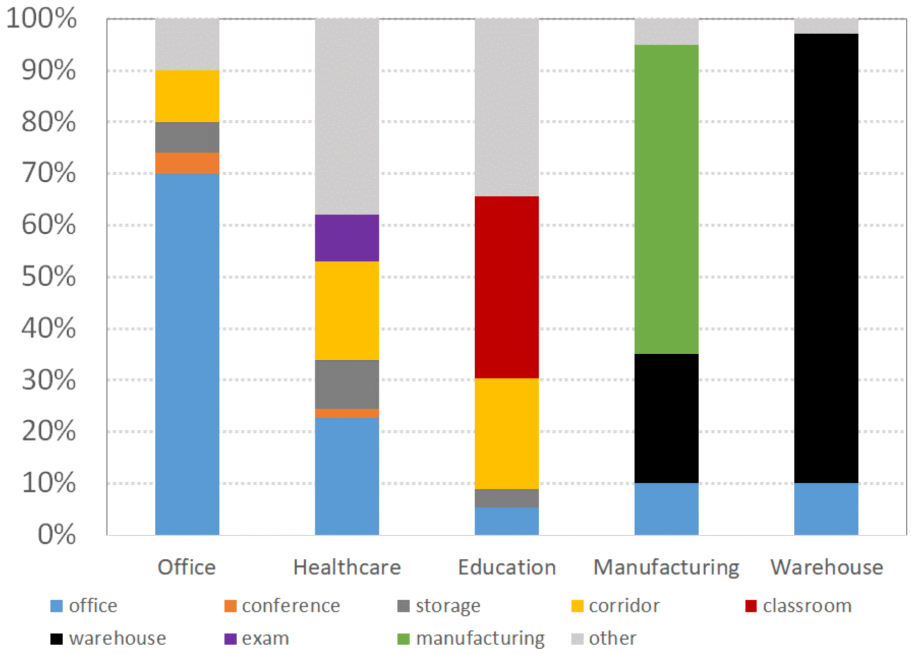

Figure 4 shows that our space types of interest comprise most of the area in each of the building types. Office buildings are predominantly comprised of office spaces (70%), followed by corridors (10%), storage (6%), conference rooms (4%), and other (10%). Healthcare buildings are predominantly comprised of other space types (38%), followed by office spaces (23%), corridors (19%), storage (10%), exam rooms (9%), and conference rooms (2%). Education buildings are predominantly composed of classrooms (35%), followed by other space types (34%), corridors (21%), offices (5%), and storage (3%). Manufacturing buildings are predominantly composed of manufacturing spaces (60%), followed by

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[16] Deru et al., "U.S. Department of Energy Commercial Reference Building Models of the National Building Stock", NREL/TP-5500-46861, February 2011.

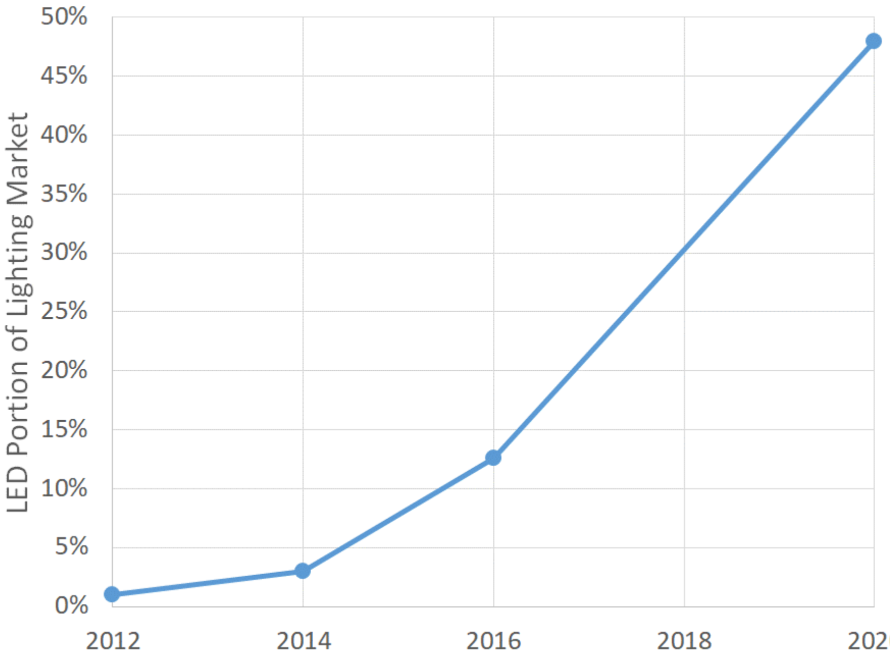
[17] eQuest 3-64 Design Development Wizard

warehouse (25%), office (10%), and other space types (5%). Warehouse buildings are predominantly composed of warehouse spaces (87%), followed by offices (10%), and other space types (3%).

LEDs and Dimmable Ballasts

LEDs are inherently dimmable, meaning their light output and corresponding lighting energy could more easily be reduced in overlit spaces than traditional fluorescent lighting systems. LEDs are rapidly increasing their share of the new and replacement lighting market. The DOE estimates (Figure 5) that in 2012, LEDs comprised only 1% of the market. However, this increased to 3% in 2014 and 12.6% in 2016.[18] The DOE further projects that by 2020, LEDs will comprise 48% of the lighting market.[19]

Figure 5: LED portion of new and replacement lighting market



Using this information, we estimated the portion of commercial spaces served by LEDs in 2020. LEDs serve a small but increasing portion of the area of each of the major building types (Figure 6). LEDs serve 10.4% of the area in office buildings, 13.2% of the area in warehouse buildings, 9.6% of the area in education buildings, and 10.4% of the area in outpatient healthcare buildings.

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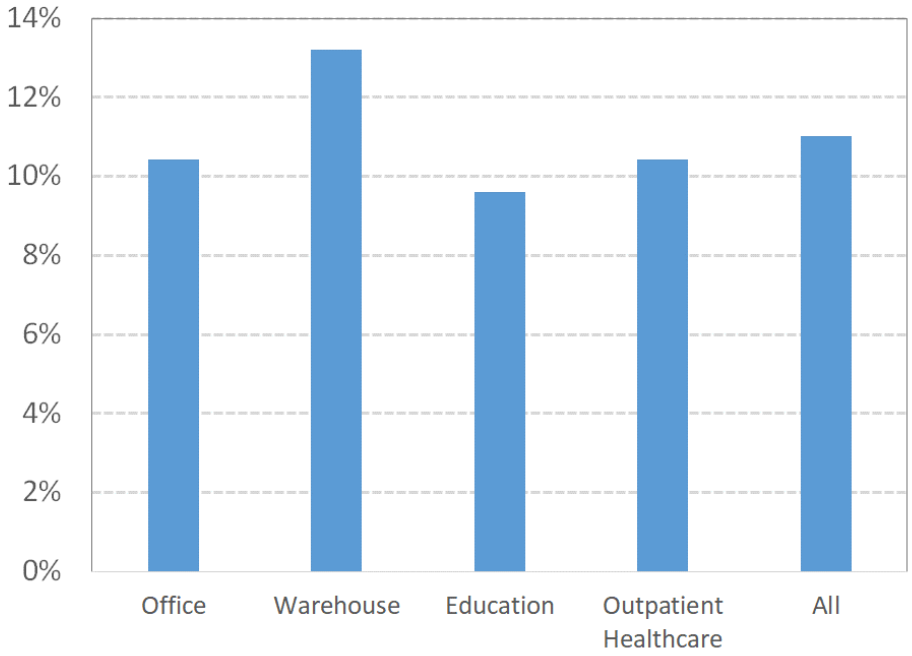
[18] State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs, Version 3.0

[19] Navigant, "Adoption of Light-Emitting Diodes in Common Lighting Applications", July 2017.

Figure 6: Proportion of area served by LEDs in commercial buildings in Minnesota



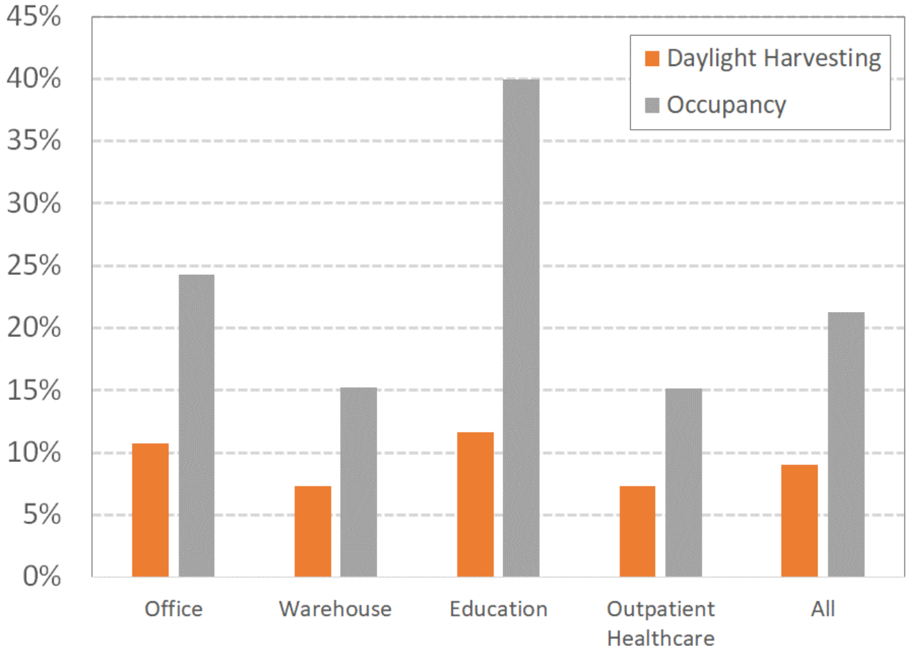
Across all the commercial building types of interest, LEDs serve 11.0% of the total area. Note that this result is slightly more conservative than the 15% assumption made within the Minnesota Potential Study. Slightly higher penetration rates exist in warehouse buildings where high bay LEDs have been implemented longer. We did not find any information about the LED penetration in manufacturing buildings.

Lighting Controls

Energy savings from task tuning will interact with other forms of advanced lighting controls (Figure 7).

Daylight harvesting is an advanced lighting control strategy that automatically adjusts the electric lighting levels when sufficient natural light is detected. This is important since the photosensor setpoint may be easily reduced in overlit spaces, thereby reducing the electric light levels during daylit periods. Figure 7 illustrates the varying penetrations of daylight harvesting by market segment.

Figure 7: The proportion of commercial buildings in Minnesota with differing advanced lighting controls.



The highest penetration of daylight harvesting is in Education, with 11.6% of education buildings having daylight harvesting. Daylight harvesting is implemented in 10.7% of office buildings, 7.3% of warehouse buildings, and 7.3% of outpatient healthcare buildings. On average, 9.0% of the commercial building types have some amount of daylight harvesting. This proportion will continue to increase due to energy code requirements for this control in spaces with natural light.

Another form of advanced lighting control is occupancy and/or vacancy sensing. These controls turn off lights during unoccupied periods. Figure 7 illustrates the varying penetrations of occupancy sensing by market segment. Of these two advanced lighting controls, occupancy sensing has the higher penetration, averaging 21.2% across the commercial building types. This control is most prevalent in Education and least prevalent in Warehouse and Outpatient Healthcare facilities.

Lighting Retrofits

It is also interesting to understand the proportion of existing buildings that have received a lighting upgrade. This would highlight the types of buildings that are more prone to lighting upgrades and those that tend to turn over their lighting less frequently. Figure 8 illustrates the relatively high proportion of Minnesota buildings that report having a lighting upgrade. Across all major building types, 22.1% of buildings report receiving a lighting upgrade,[20] with Outpatient Healthcare having the highest penetration (37.7%) and Warehouses the lowest penetration (10.4%) of lighting upgrades. For Education

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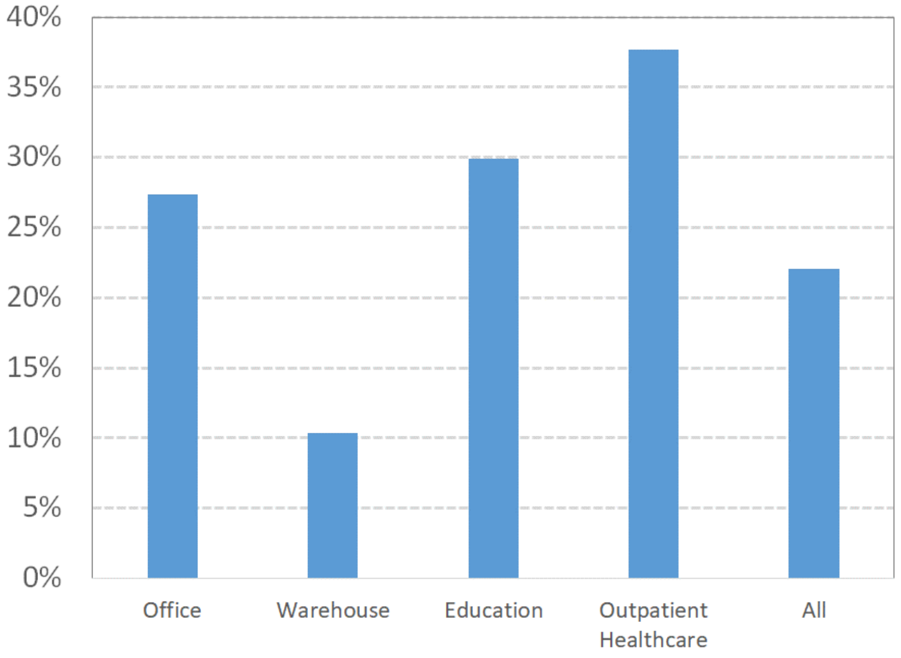
[20] Due to the referenced CBECS data being from 2012, it is likely that these upgrades were from an existing fluorescent system.

buildings, 29.9% reported having lighting upgrades and 27.4% of Office buildings reported having lighting upgrades.

Figure 8: Proportion of commercial buildings in Minnesota with lighting upgrades.

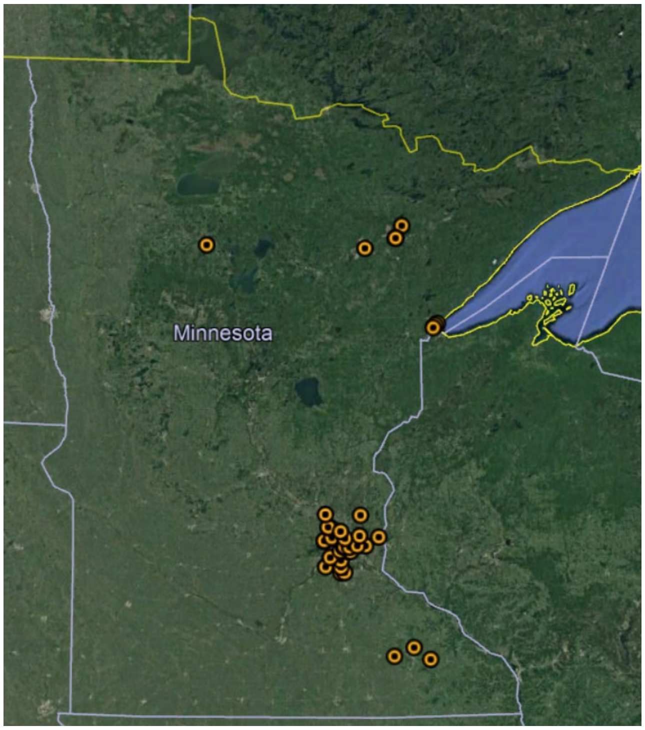


Site Visits

Building and System Summary

We visited a total of 36 buildings across Minnesota (Figure 9).

Figure 9: Map of visited buildings.



The sites were predominately clustered around population centers, such as Minneapolis, St. Paul, Rochester, and Duluth, with several additional sites in smaller towns.

Within the sites, we visited buildings from each of our target building types (Table 9). We visited 9 office buildings, 9 education buildings, 10 warehouse and storage buildings, and 8 manufacturing buildings. We originally intended to visit 45 buildings total, as detailed in the Methodology section of this report. However, it became clear as we analyzed the data that we would be able to meet a 95% confidence interval targets with fewer site visits. We therefore lowered our target to 37. We also eliminated an Education site because of its extremely low light levels and atypical lighting types for an education space, leaving a total of 36 sites.

Table 9: Number of buildings visited by building type.

Building Type	Number Visited
Office	9
Education	9
Warehouse & Storage	10
Manufacturing	8

Anecdotally, the Manufacturing facility staff were just as interested in the light levels of their manufacturing areas as they were about the office space. While manufacturing areas were outside the scope of the project, this interest combined with the high lighting requirements of these spaces would indicate opportunity for a program to support light level optimization in manufacturing production.

Within these building types, we measured light levels in each space type (Table 10). Although we set out to visit 44 spaces for each space type category, we did not meet this target for every category except Private Office. This is due to the reduction in the number of site visits overall (reducing 44 to 37) and averaging below the number of expected unique spaces per building. We measured light levels in 28 open offices, 50 private offices, 36 conference rooms, 27 warehouses, 25 corridors, and 19 classrooms.

Table 10: Number of spaces visited by space type.

Space Type	Number Visited	Target Sample
Open Office	28	44
Private Office	50	44
Conference Room	36	44
Warehouse	27	44
Corridor	25	44
Classroom	19	44

Note that despite not meeting our original target sample, we were still able to meet our target precision with respect to statistical significance. This is because our assumptions in estimating the target sample size were, in retrospect, conservative. More specifically, a higher mean illuminance led to reduced sample necessary to achieve our confidence interval target.

For each space, we documented the lighting power, allowing us to quantify the lighting power density (LPD) of each space type (Table 11).

Table 11: Lighting power density by primary lighting type for each space type.

Space Type	Lighting Power Density (W/ft^2)	ASHRAE 90.1-2007 LPD (W/ft^2)	ASHRAE 90.1-2007 % Decrease	ASHRAE 90.1-2016 LPD (W/ft^2)	ASHRAE 90.1-2016 % Decrease
Open Office	0.65	1.1	41%	0.61	-7%
Private Office	0.73	1.1	34%	0.74	2%
Conference Room	0.58	1.3	55%	0.97	40%
Warehouse	0.27	0.9	70%	0.33	17%
Corridor	0.45	0.5	9%	0.41	-11%
Classroom	0.60	1.4	57%	0.71	15%

It is interesting to compare the LPD's in our LED-lit spaces to those from ASHRAE 90.1-2007 and 2016. The space-by-space method of the 2007 represents an all-fluorescent baseline, while the 2016 version represents a predominately LED baseline. For every space type our space type's LPD is significantly lower than the 2007 code version, ranging from 9% in corridors to 70% lower in warehouses. Our space types' LPDs were more in line with the 2016 code version. In fact, they were 7% higher than the open office standard and 11% higher than the corridor standard. Conference rooms remained an area where installed LEDs resulted in LPDs significantly lower (40%) than code.

For each space, we documented the amount of lighting power controlled by occupancy or photosensors. We then summarized the proportion by lighting power of each space type with these controls (Table 12).

Table 12: Percentage of total lighting power controlled by occupancy or photosensors for each space type.

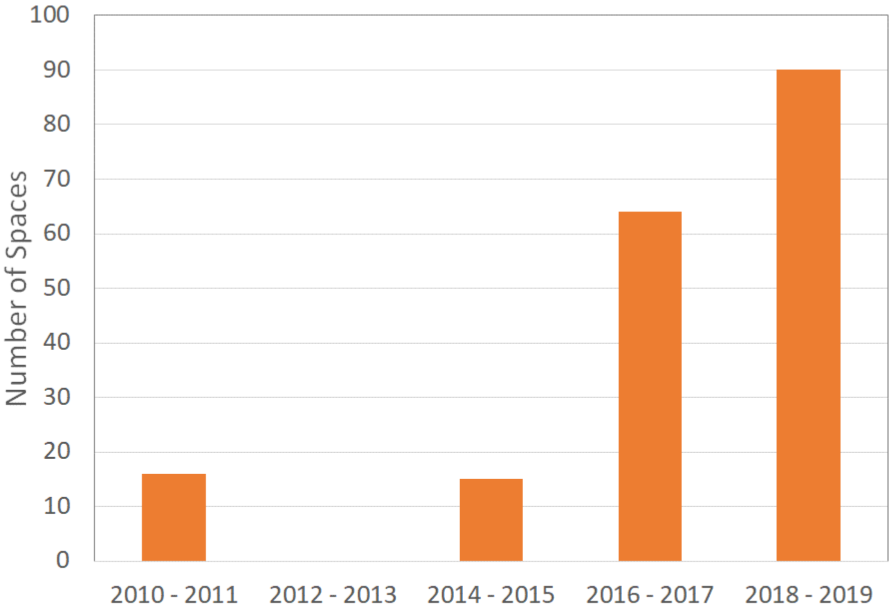
Space Type	Occupancy Sensor	Photosensor
Open Office	30%	0%
Private Office	2%	0%
Conference Room	13%	0%
Warehouse	24%	0%

Space Type	Occupancy Sensor	Photosensor
Corridor	12%	0%
Classroom	45%	0%
Total	***24%***	***0%***

Occupancy sensors controlled 24% of the lighting power in the spaces we characterized. This proportion was highest in Classroom spaces (45%) but was prevalent in all other space types except Private Offices (2%). Occupancy sensors controlled 30% of the lighting power in open offices, 13% in conference rooms, and 12% in corridors. Photosensors were much less prevalent, controlling none of the lighting power in the spaces we characterized. This information will be used when extrapolating the potential energy savings of tuning light levels in Minnesota.

For each space, we documented the year that the lighting system was installed or renovated (Figure 10). Sixteen spaces had the lighting installed in 2010-2011; 15 spaces had it installed in 2014-2015; 64 spaces had the lighting installed in 2016-2017; 90 spaces had the lighting installed in 2018-2019.

Figure 10: Year of installation or renovation.



In most characterized spaces (83%), the lighting systems were installed between 2016 and 2019. This trend is indicative of the increasing prevalence of LEDs in the market over time. This large proportion is also likely due to sample bias of facility owners with newer systems being overrepresented in our email sample.

A few other general lessons from our site visits included:

- We were able to conduct our site visits of Education facilities more easily because our site visits occurred in the summer. This is applicable to a potential program as they may want to focus outreach to this facility type during the summer months as well.
- The worship areas in churches would typically not be good candidates for light level adjustment. However, many churches have associated schools and offices, making them candidates both for our study as well as a light level adjustment program.

Description of Commercial Building Light Levels

We quantified the mean illuminance for our sample by space type (Table 13). The mean of average illuminance was 49.6 fc (18.3 fc standard deviation) for open offices, 47.7 fc (17.7 fc standard deviation) for private offices, 45.2 fc (17.9 fc standard deviation) for conference rooms, 31.2 fc (21.1 fc standard deviation) for warehouses, 34.5 fc (16.7 fc standard deviation) for corridors, and 48.0 fc (15.9 fc standard deviation) for classrooms. The relative precision ranged between 5.0-8.4 fc.

Table 13: Mean, standard deviation, and relative precision average illuminance (fc) by space type.

Space Type	Mean	Standard Deviation	Relative Precision at 95% CI
Open Office	49.6	18.3	7.1
Private Office	47.7	17.7	5.0
Conference Room	45.2	17.9	6.0
Warehouse	31.2	21.1	8.4
Corridor	34.5	16.7	6.9
Classroom	48.0	15.9	7.7

Note that we were able to increase our relative precision criteria from 90% to 95%. We then calculated the degree to which the mean illuminance differed from the IES recommendation for each space type, expressed as the percent reduction needed to bring the mean into agreement with the recommendation (Table 14).

Table 14: Mean, IES recommendation, and percent reduction average illuminance (fc) by space type.

Space Type	Mean	IES Recommendation	% Reduction
Open Office	49.6	30	40%
Private Office	47.7	30	37%
Conference Room	45.2	30	34%
Warehouse	31.2	30	4%
Corridor	34.5	5	86%
Classroom	48	40	17%

For all space types, the mean illuminance was higher than the IES recommendation. This means that energy savings could be captured by bringing the two into agreement. In Open Offices, Private Offices and Classrooms, this illuminance reduction potential was 40%, 37%, and 17%, respectively. This reduction potential is significant, considering the quantity of these space types in Minnesota. Conference Rooms were also very overlit, needing a reduction of 34% to bring their mean illuminance into agreement with the IES recommendation. Corridor (86%) spaces were the most overlit. There is less opportunity for aggregate energy savings in these spaces due to their smaller portion of overall building area. In addition, the IES recommendation of 5 fc for corridor spaces may be considered too aggressive of a reduction by facility staff and building occupants, thereby reducing the energy savings potential. Warehouse was the only space type with a mean illuminance essentially on par with the IES recommendation (4% reduction). This may be due to a higher focus since lighting energy cost in a warehouse are a significant operating expense.

When the mean illuminance and IES recommendations are presented visually (Figure 11), the difference between the two is more striking.

The error bars on the mean illuminance represent the 95% confidence interval. Except for Warehouse, all of the IES recommendations fall outside of these bounds. This indicates that our estimated mean illuminance is statistically different than the IES recommended illuminance and that those spaces were all overlit.[21] Since the Warehouse recommendation falls within these bounds, we cannot be as certain whether this space type is over or underlit.

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[21] Alpha=0.1. Analysis of other influential effects on average illuminance in spaces was out of scope for the study. It is possible that unaccounted confounding effects would increase the uncertainty of estimated mean illuminance shown here.

Figure 11: Mean versus IES recommended illuminance.

We tracked whether a given space was lit by tubular LEDs or LED fixtures. Figure 12 compares the mean illuminance by space type and for all displayed data for different fixture types.

Figure 12: Mean illuminance for different fixture types

The general trend is lower illuminance levels in spaces lit by whole fixtures as compared to TLEDs. Overall, the illuminance for spaces lit by whole fixture LEDs was 8% lower than those lit by TLEDs.

However, it should be noted that the confidence intervals overlap significantly for these comparisons. The general trend may be indicative of a more thoughtful design and flexibility for spaces lit by whole fixture LEDs.

We tracked whether the LEDs in each space were installed as part of new construction or a retrofit project. Figure 13 compares the mean illuminance by space type and for all displayed data for different installation types.

Figure 13: Mean illuminance for different installation types

Note that there was insufficient sample for new construction classrooms, so this space type is not displayed. The general trend is lower illuminance levels for spaces with LEDs installed as part of new construction as opposed to retrofit projects. Overall, the illuminance for LEDs installed for new construction was 11% lower than those for retrofits. However, it should be noted that the confidence intervals overlap significantly for these comparisons. The general trend may be indicative of a more thoughtful design and flexibility for new construction spaces.

Expected Savings Estimates

Following the assumptions outlined in the Methodology section, the final estimated achievable savings potential from light level adjustment incentive programs in Minnesota are shown in Table 15.

Table 15: Achievable potential savings from light level adjustment in Minnesota.

Building Type	Estimated electricity savings (MWh)	Annual dollar savings ($)	Avoided GHG emissions (tCO2 eq.)
Office	95,520	$10,354,346	86,827
Education	45,433	$4,924,901	41,298
Manufacturing	9,183	$995,481	8,348
Warehouse	16,805	$1,821,677	15,276
Total	***166,941***	***$18,096,405***	***151,749***

In total, we estimate that adjusting light levels could potentially save Minnesota approximately 167,000 megawatt hours annually, with most of these savings coming from the Office and Education sector. This energy savings is equivalent to 15,500 typical Minnesota household's annual electric consumption,[22] reducing greenhouse gas emissions by approximately 152,000 tons of carbon dioxide equivalent, or the equivalent of taking 32,000 passenger vehicles off the road for a year.[23] This energy savings equates to over $18 million cost savings to Minnesota businesses. Note that this savings potential estimate assumes 88% of Minnesota lighting across these facilities is first upgraded to LEDs by 2035 and that 58% of these lights are easily tunable.[24] It also assumes a program achievability factor of 57.5%.[25]

When normalized to a per square foot basis, the technical potential for energy and peak demand savings may be estimated for a given project (Table 16).

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[22] Annual electricity consumption of typical Minnesota household of 10,766 kWh/yr. U.S. Energy Information Administration (2012). "Average monthly residential electricity consumption, prices, and bills by state." http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3

[23] Annual greenhouse gas emissions from passenger vehicles of 4.75 tCO2. U.S. Environmental Protection Agency (2011). "Greenhouse Gas Equivalencies Calculator." https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

[24] Navigant, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications", December 2019.

[25] Minnesota Energy Efficiency Potential Study: 2020-2029. CARD Final Report, contract #121430. https://mn.gov/commerce/policy-data-reports/energy-data-reports/?id=17-361187

Table 16: Typical electricity and peak demand savings.

Building Type	Typical Electricity Savings (kWh/ft^2)	Typical Peak Demand Savings (W/ft^2)
Office	1.03	0.23
Education	0.46	0.13
Manufacturing	0.14	0.03
Warehouse	0.17	0.04

The typical electricity savings range from 0.14 kWh per square foot for Manufacturing buildings to 1.03 kWh per square foot for Office buildings, with typical peak demand savings that range between 0.03 W per square foot and 0.23 W per square foot, respectively. On a project-by-project basis, the energy savings from tuning light levels of a lighting system without other controls may be estimated as:

$$\Delta Q_{tune} = \%_{reduction} * Q_{tot}$$

Where:

ΔQ_{tune} is the electricity savings from reducing light levels in kWh,

$\%_{reduction}$ is the percent reduction of maximum lighting power, and

Q_{tot} is the annual electricity consumption of the tuned lighting system in kWh.

Note that the percent reduction of maximum allowable lighting power, often called high end trim, is closely approximated by the percent reduction in light levels. Reasonable percent reductions by space type may be found in Table 14 for LED-lit spaces. The annual electricity consumption may be estimated as:

$$Q_{tot} = P \cdot t$$

Where:

P is the connected lighting power in kW, and

t is the annual operating time in hrs.

For systems with other controls, the energy savings from tuning light levels interacts with the savings from the other controls technologies. The most prevalent controls are occupancy controls with photocontrols becoming increasingly important in new construction projects due to code requirements. The energy savings from tuning light levels of a lighting system with these controls may be estimated as:

$$\Delta Q_{tune,int} = f * \Delta Q_{tune}$$

Where:

$\Delta Q_{tune,int}$ is the interactive electricity savings from reducing light levels in kWh, and

f is the controls interactivity factor.

The controls interactivity factor may be approximated as:

$$f = 1 - \%_{oc} - \%_{pc} + \left(\%_{oc} * \%_{pc}\right)$$

Where:

$\%_{oc}$ is the percent savings from occupancy controls, and

$\%_{pc}$ is the percent savings from photosensor controls.

Table 17 summarizes typical percent savings from occupancy and photosensor controls,[26] and Table 18 summarizes the corresponding interactivity factors. Typical percent savings range from 23% (office) to 35% (warehouse) for occupancy controls and range from 28% (warehouse) to 49% (education) for photosensor controls.

Table 17: Typical percent savings for occupancy and photosensor controls.

	Typical Percent Savings	
Building Type	**Occupancy Control**	**Photosensor Control**
Office	23%	38%
Education	31%	49%
Manufacturing	no data	no data
Warehouse	35%	28%

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[26] Williams et al., "A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings", 2011, Lawrence Berkeley National Laboratory.

Table 18. Typical interactivity factors for occupancy and photosensor controls.

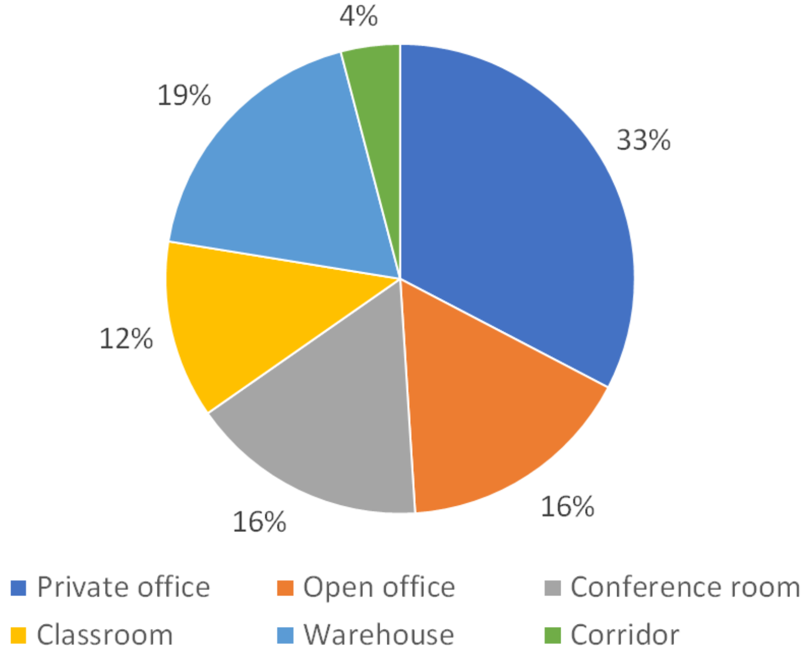
Building Type	Interactivity Factor Occupancy Control Only	 Photosensor Control Only	 Both
Office	0.77	0.62	0.48
Education	0.69	0.51	0.35
Manufacturing	no data	no data	no data
Warehouse	0.65	0.72	0.47

Note that controls interactivity will reduce savings most significantly (between 49% and 65%) in Education spaces due to the high prevalence and savings from occupancy and photosensors. Offices and Warehouses spaces have similar, lower savings reductions of between 23% and 53%.

Occupant Surveys

Occupant surveys focused on measuring satisfaction with light levels, visual comfort and controllability of workspace lighting following task tuning. We received occupant survey responses representing 49 unique spaces across 24 buildings. Figure 14 shows the breakdown of responses by space type.

Figure 14: Occupant survey responses by space type.



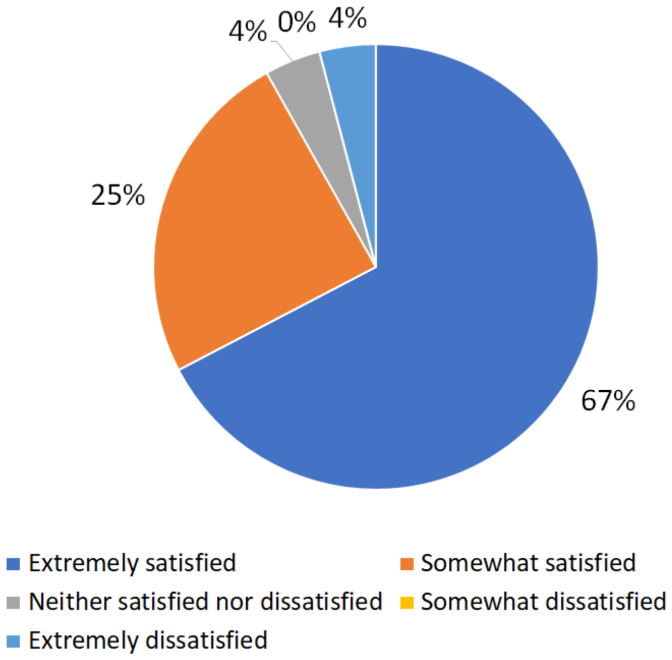
The largest proportion of survey responses were from private offices (33%). However, we also received significant proportions from open office (16%), warehouse (19%), conference room (16%) and classroom (12%).

Additionally, over two-thirds (68%) of respondents were within 15 feet of a window. This was surprising since no daylighting controls were reported, despite retrofits or construction being completed relatively recently under building codes with daylighting control requirements. It is also important to note that natural light in these spaces would increase light levels beyond the electric lighting components measured within this study, which themselves were already high.

The respondents reported controls like those that we found during our site visits, illustrating their general perception of controls was accurate. This predominately included manual on/off switches with some operable blinds and shades for glare control. There were limited dimmer switches and occupant sensors.

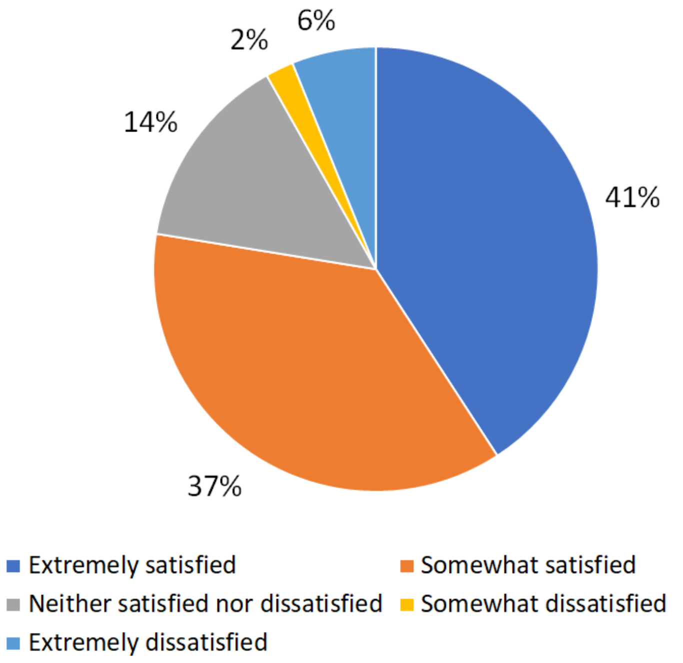
The following figures summarize the respondent's level of satisfaction with the amount of light (Figure 15), the ability to control the light level (Figure 16), and the visual comfort (Figure 17) provided by the light in their workspace.

Figure 15: Level of satisfaction with the amount of light.



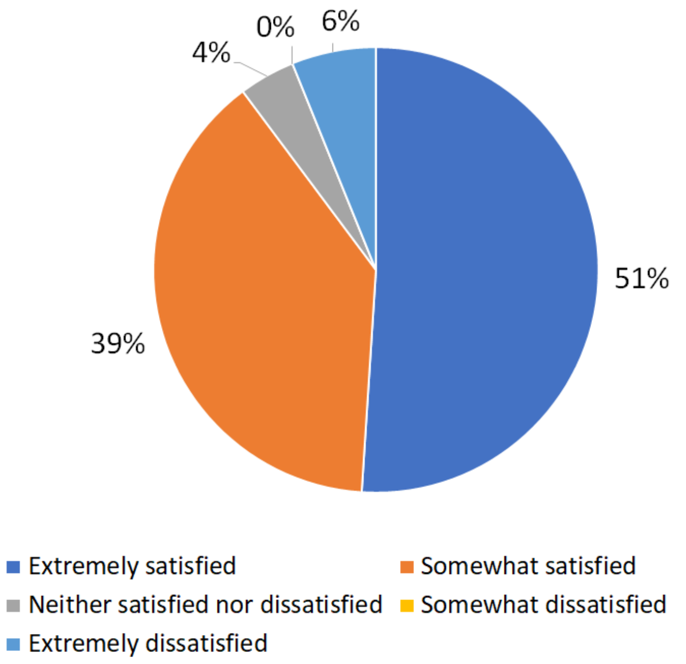
Over two-thirds (67%) of respondents were Extremely Satisfied, while one-quarter (25%) were Somewhat Satisfied with their light level.

Figure 16: Level of satisfaction with ability to control overhead lighting.



Four out of five respondents were either Extremely (41%) or Somewhat (37%) Satisfied with their ability to control their lighting despite limited manual dimming.

Figure 17: Level of satisfaction with visual comfort.



Nine out of ten respondents were either Extremely (51%) or Somewhat (39%) Satisfied with the visual comfort provided by their lighting.

Figure 18 summarizes respondent's perception that their lighting enhanced or interfered with their ability to do their work.

Figure 18: Perception that lighting enhanced or interfered with ability to do work.

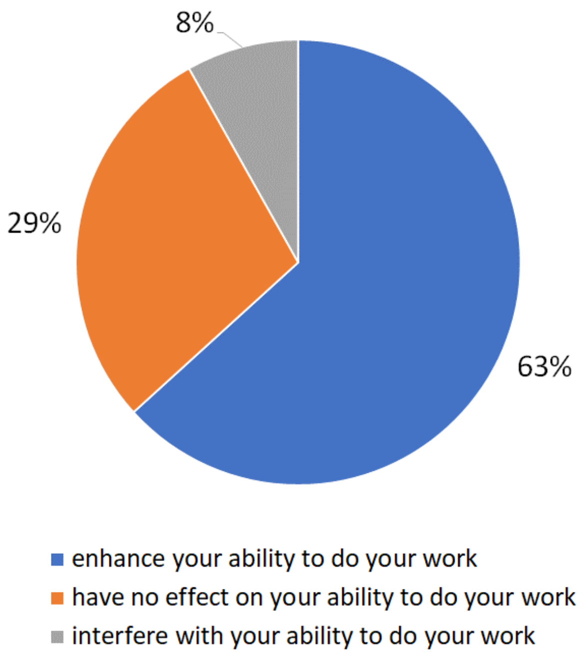


Table 19: Average score by metric and space type.

Space Type	Light Level	Control	Comfort	Productivity
Private office	1.6	1.8	1.7	1.8
Open office	1.5	2.6	2.0	2.5
Conference room	1.3	1.3	1.5	1.5
Classroom	2.2	2.0	2.2	2.3
Warehouse	1.1	2.1	1.4	1.4
Corridor	1.5	2.5	1.5	n/a
Overall	***1.5***	***2.0***	***1.7***	***1.9***

Nearly two-thirds (63%) of survey respondents thought their lighting enhanced their ability to do their work. Across all metrics, survey respondents were generally satisfied with their LED lighting. Table 19 summarizes the average score for each metric by space type. Note that a score of 1 is extremely satisfied, while 5 is extremely dissatisfied.

The overall score for light level (1.5) was great. Warehouse had the best light level score. This was interesting considering this space was not overlit per IES recommendations, suggesting that light levels in line with these recommendations are better from an occupant satisfaction standpoint. Classroom had the worst light level score, which may reflect the increased importance of light level in creating the best learning environment possible.

The overall score for control (2.0) was good. Conference rooms had the best overall control score which is likely related to the high level of controllability in these spaces associated with Audio-Visual scenes. Private office also had a high control score, which is likely due to a single occupant having ownership of their lighting. Open offices had the worst controllability score, which is likely to the limited control in these spaces across multiple occupants and partitions negatively impacting light distribution.

The overall score for comfort (1.7) was also great. The trends were very similar to light level, which suggests a high correlation between light levels and visual comfort.

The overall score for productivity (1.9) was also good. Warehouses had the best overall score. Open offices had the worst productivity score, which may reflect less optimal lighting design in these spaces driven by a designer's inability to predict where occupants will sit with respect to the lighting fixtures.

Expedited Assessment

Reduced Sampling Approach

The results of simulating three potential expedited sampling approaches are summarized in Table 20. Overall, Method 1, which involved calculating the mean difference in light level measurements, was the most accurate for luminaire configurations Type A, B and C.[27] On average, for these configurations, using Method 1 will capture illuminance estimates within 5% of what would be estimated using the full IES protocol. However, Method 3, which involved taking light level measurements for one random point of each type and estimating illuminance with the IES formulas, was more accurate for luminaire configuration Type D, E and F.[27] For these luminaire configurations, Method 3 had a mean deviation of between 2 and 10% compared to the full IES protocol. Method 2, which involved calculating the mean light levels for one random point of each type, was the least accurate. Although we report results for configuration types E and F here, given the very small sample sizes, we cannot make any conclusions about whether the patterns observed would apply more generally.

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[27] DiLaura et al., The Lighting Handbook, Tenth Edition, 2011.

Table 20. Mean absolute percent deviation from full illuminance measurement for each expedited sampling approach. numbers in parentheses represent bounds of 95% bootstrapped confidence intervals.

Luminaire configuration type	Sample size	Method 1: Mean for all points	Method 2: Mean for one point of each type	Method 3: IES formula using one point of each type
Type A	78	5.6% *(4.6, 6.59)*	10.6% *(9.0, 12.1)*	7.6% *(6.3, 8.3)*
Type B[28]	52	0 (NA)	13.5% *(9.71, 16.7)*	13.5% *(9.79, 16.7)*
Type C	42	3.6% *(2.4, 4.67)*	15% *(12.57, 17.4)*	14.6% *(10.4, 17.8)*
Type D	9	15.6% *(8.6, 22.2)*	19.7% *(13.4, 25.8)*	10% *(1.5, 15.5)*
Type E[29]	3	10.1% *(NA)*	21.2% *(NA)*	9.3% *(NA)*
Type F[29]	1	3.1% *(NA)*	6.8% *(NA)*	1.8% *(NA)*

These results suggest that for the most common luminaire configuration types we observed in this study (Types A, B and C), Method 1 could be used as an expedited assessment to estimate light levels. For example, if a classroom with configuration Type A were measured as having an average illuminance of 50 fc using the full IES protocol, we would expect Method 1 to produce an estimate within 6.6% of that 95% of the time or within 3.3 fc. For the same space, Method 2 should generate an estimate within 8.3% of 50 fc for the same space or within 4.2 fc. This level of accuracy is smaller than the degree of overlighting in most space types, meaning it may be used to determine whether a space is overlit. But it is also important to note that any expedited sampling procedure sacrifices accuracy and will misrepresent the light levels to some degree, especially those with uneven light levels across the space. The boxplots in Figure 19 provide an indication of the variation in the individual estimates for each sampling method for the most common luminaire configurations.

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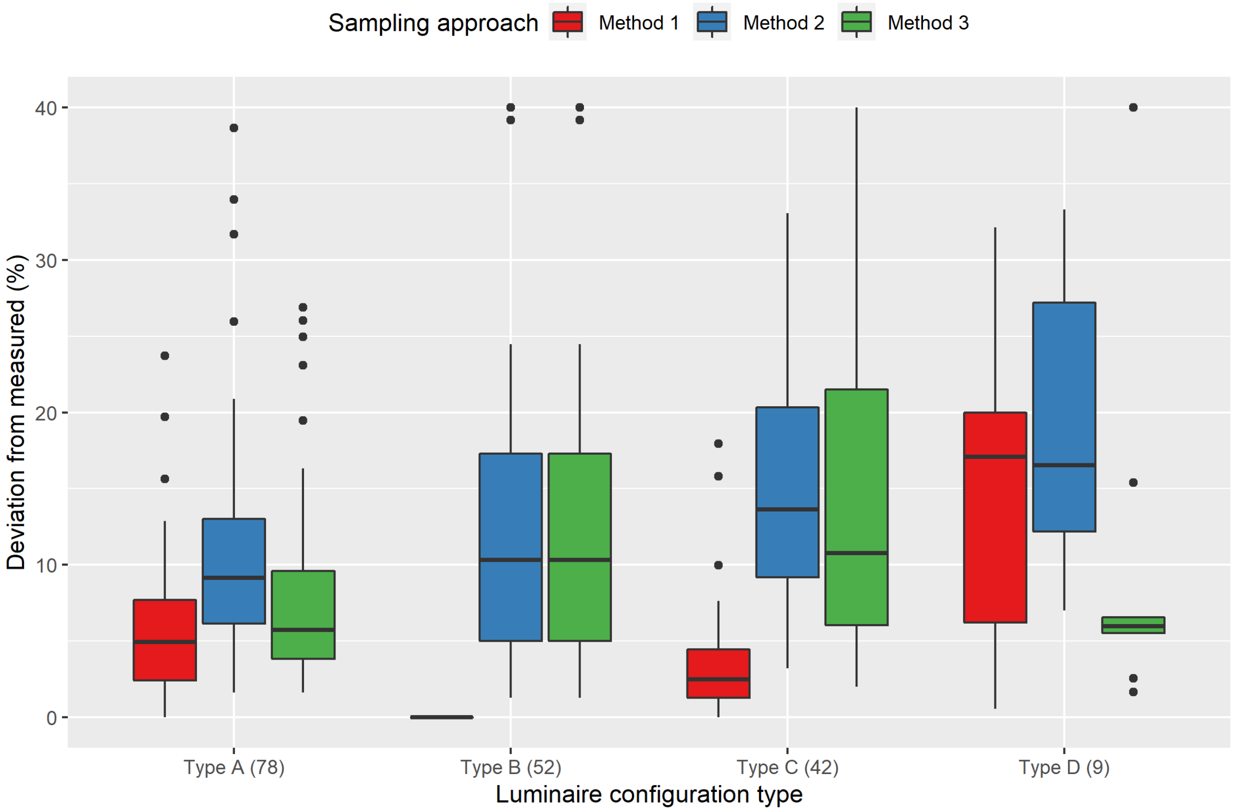
[28] For this luminaire configuration the IES method calculating method was identical to method 1 resulting in a no difference between estimates. Also, since there is only one point type for this configuration the estimates for Method 2 and 3 are identical.

[29] Sample sizes for these luminaire configurations were too small to calculate meaningful confidence intervals.

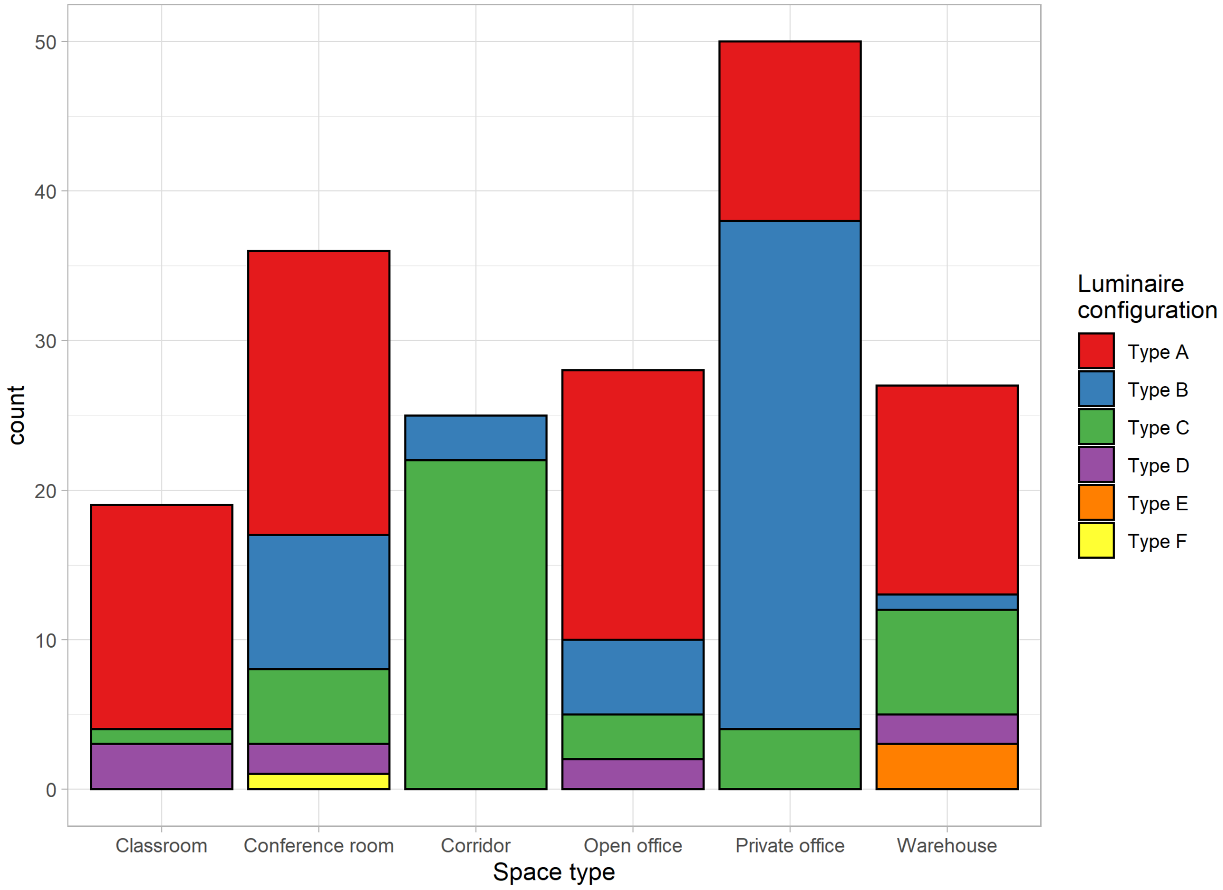
Figure 19. Box plots provide indication of how much average illuminance estimates deviated for each sampling method for the most common luminaire configuration types.



Horizontal lines are medians, boxes contain middle 50% of values, vertical lines show range for 99% of the values and points represent outliers. Numbers in parentheses by x axis labels indicate sample size.

To help evaluate the practical implications of these results, we looked at which space types each luminaire configurations were most likely to be found based upon this study. These counts of luminaire configuration types by space types are shown in Figure 20. We see, for example, that classrooms are mostly Type A configuration, and private offices Type B and corridors Type C. This suggests it is possible to make simple guidelines for expedited sampling based upon space types. For example, to reduce staff training time, a program could recommend an expedited sampling approach with the assumption that all classrooms, corridors and private offices be sampled using the protocols for the mostly likely luminaire configuration, i.e., A, B, and C respectively.

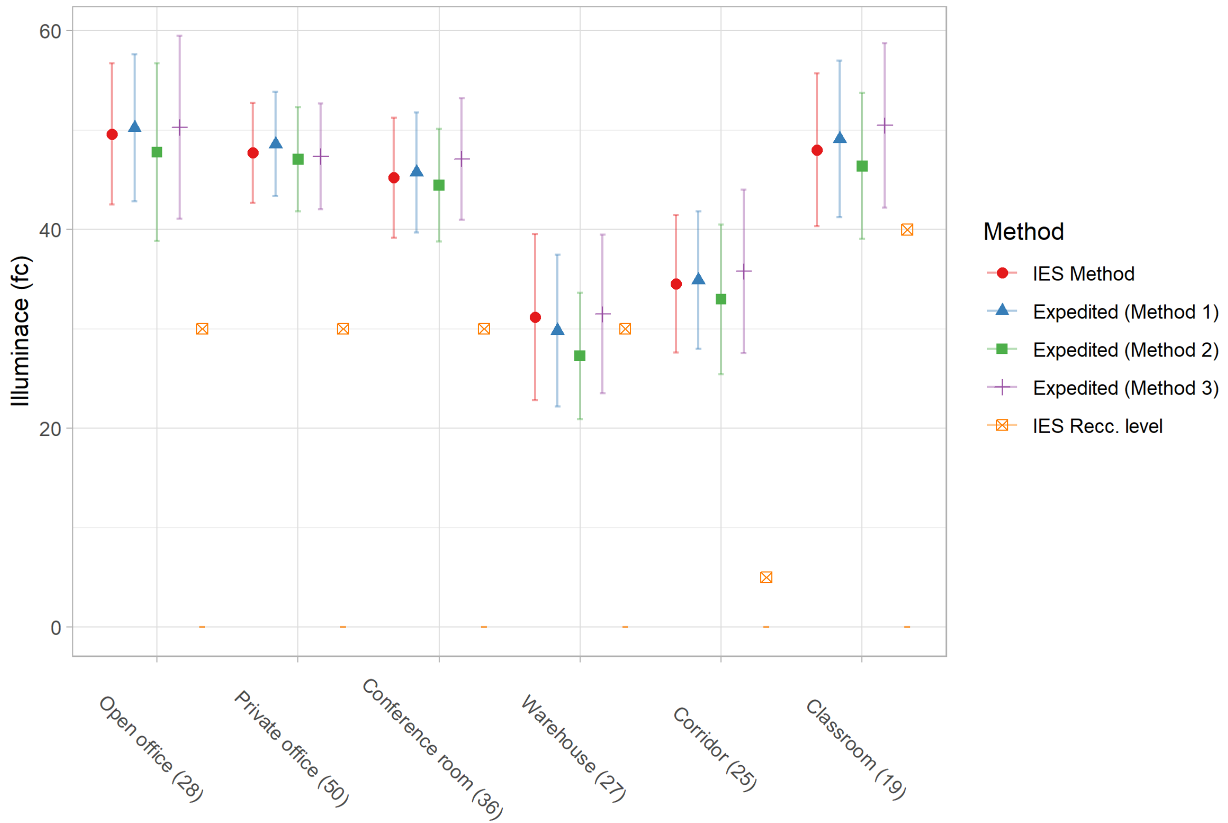
Figure 20. Count of luminaire configuration type for each space type.



Overall, a practical take-away from this investigation is that Method 1 yields the most accurate results for the most common luminaire configurations (Types A, B and C). For other configurations it may be better to use Method 3. However, given the smaller sample sizes for luminaire configurations D, E, and, F, it is harder to generalize about what method would be best.

Although expedited sampling methods will be less accurate for estimating the illuminance of individual rooms, when sampling across multiple rooms, we found that each method should produce reasonable estimates of mean illuminance. After simulating the estimation of mean illuminance for each space type we found that each of the methods produced similar overall estimates (Figure 21). Method 1 appears to slightly overestimate illuminance for most space types, Method 2 appears to underestimate illuminance, and Method 3 produces results that are closest to the actual measured. Overall, these results correspond to the patterns observed in the mean percent of each expedited method: Methods 1 and 3 are more likely to produce accurate estimates of room illuminance compared to Method 2.

Figure 21. Estimated mean illuminance by space for simulated expedited sampling methods



Numbers in parentheses by x axis labels indicate sample size.

We therefore conclude that a building operator, contractor or program implementer could save time by either measuring fewer points or using a simplified calculation without significantly sacrificing the overall accuracy of the calculated illuminance.

Photometric Analysis

Overall, we found that photometric analysis does a good job of estimating light levels. Table 21 summarizes the 10 modeled spaces and the degree to which the model and measured illuminances agreed.

Our models were on average within 4.4% of measured illuminance and ranged from 0.85% to 8.9%.

We further evaluated the impact of tall partitions in open office spaces and tall racking in warehouse spaces by adding these objects into select photometric models. We found that modeled illuminance of spaces with tall partitions or tall racking were 10-15% lower than measured illuminance. This is likely due to our field staff avoiding shaded areas when recording measurements and difficulty in recording some measurements required by the luminaire configuration type due to the physical barriers themselves. It is best practice to include these physical elements in photometric models whenever possible to better estimate light levels under actual conditions.

Table 21: Measured and modeled illuminance by fixture type for each space type.

Space Type	Fixture Type	Measured Illuminance (fc)	Modeled Illuminance (fc)	% Difference
Open Office	Whole Fixture	34.2	35.4	3.5%
Open Office	Tubular LED	32.0	31.1	2.8%
Private Office	Whole Fixture	63.7	66.2	3.9%
Private Office	Tubular LED	86.5	84.1	2.8%
Warehouse	Whole Fixture	64.2	59.0	8.1%
Warehouse	Tubular LED	35.6	35.3	0.85%
Warehouse	Tubular LED	18.1	17.9	1.1%
Warehouse	Tubular LED	26.9	25.8	4.1%
Classroom	Whole Fixture	57.5	53.0	7.8%
Classroom	Tubular LED	55.0	59.9	8.9%

For LED fixtures, IES files are available for download on a manufacturer's website or may be requested from a manufacturer. These files may be used directly in photometric models without modification. Additional steps are required when defining fluorescent fixtures that have been retrofit with a tubular LED lamp. It is important to locate and download a manufacturer's specification sheet for the specific LED lamp to confirm the lumens per lamp. Keep in mind that efficacy tends to improve with next generation products which can impact the lumens per lamp value. The IES file for the existing fluorescent fixture must also be obtained. Within the fluorescent fixture's IES file, the fluorescent lamp lumens are replaced by the LED lamp lumens. This is easily done through the fixture definition interface within a software program like AGi32. Some LED lamp manufacturers provide IES files that have already made this revision but should only be used if the fixture type is consistent with the installed luminaires.

An IES file also includes the fixture's efficiency which impacts the actual lumens emitted from the fixture. Fixture efficiency is often detailed on a manufacturer's specification sheet. Within the model, the lumens that effectively illuminate the space are a product of the number of lamps, the lumens per lamp, the efficiency, and the light loss factor (LLF). As our goal was a photometric comparison of field measured values, a LLF of 1.0 was selected. Any light loss due to dirt depreciation or lumen depreciation was minimal based on field observations of clean fixtures and confirmation that the installed fixtures or LED lamps had relatively low hours of operation to date. When completing photometric analysis for lighting design purposes, the mean illuminance over the life of a fixture is generally the goal and an LLF of 0.8 – 0.9 is a more typical value. Using these lower LLF values in photometric models would lead to a proportional decrease in predicted illuminance levels. This would yield higher task tuning setpoints and lower energy savings. We recommend using these lower LLFs as they are a conservative assumption that would minimize occupant visual discomfort as the LED light output decreases over the fixture lifetime.

We conclude that photometric analysis is a useful tool for evaluating illuminance values and identifying opportunities for task tuning and associated energy savings. Although models are less accurate than field measurements, the reduced time involved justifies the relatively small tradeoff in accuracy. Task tuning is likely to be perceived as providing satisfactory light levels in spaces with high light level uniformity, such as classrooms or private offices. This is particularly true if conservative assumptions are made while modeling (e.g. LLF of 0.8-0.9, reasonable reflectance values). In situations where model inputs are unknown (such as partition heights and locations), the degree to which lights are task tuned based on models should be reduced. For example, if the model predicts a space will be 20% overlit, the lights could be task tuned by 10-15%. This may be relaxed in spaces with task lights since occupants may supplement the ambient lighting to provide higher light levels only where necessary. In warehouse spaces with tall racking, photometric models that evaluate vertical illuminance on racking can be equally important to horizontal illuminance in circulation areas. However, since we did not measure vertical illuminance values, we could not assess the degree to which our models agreed with these measurements.

Occupant Satisfaction Correlation

Unfortunately, there was insufficient data for correlating the Neither Satisfied nor Dissatisfied, Some Dissatisfied and Extremely Dissatisfied levels with how overlit a space was. This was due to the high level of occupant satisfaction in the spaces we studied. However, the averaged percentage overlit was only 6% for Extremely Satisfied, but 27% for Somewhat Satisfied respondents. This suggests that better occupant survey scores correlate to light levels in better agreement with IES recommendations. Although occupant surveys alone are insufficient to assess the light levels in a building, they are an important tool for service providers. We recommend deploying them to the extent reasonable on lighting projects. Appendix D: Occupant Survey may be used as a template for getting started. This is particularly important as high levels of reported satisfaction lead to project success from a customer retention perspective, and possibly correlate to higher energy savings due to lower light levels.

Minnesota Program Interviews

We completed two interviews with investor owned utility staff, three interviews with muni/coop staff, and one interview with a program implementation contractor. We also interviewed one representative from the Northwest Energy Efficiency Alliance, a national leader in lighting market transformation.

Commercial lighting programs are a major driver of energy savings for Minnesota CIPs, representing 60-70% of C&I portfolio savings for some interviewees. Most lighting projects involve retrofits of existing spaces. New construction projects represent a smaller share of program participation, contributing 10-15% of lighting program savings. Full lighting redesign in existing buildings represents 10-15% of commercial lighting program savings. Lighting projects in tenant fit-outs are not common in most areas, though may be slightly more prevalent in urban/suburban areas (reported maximum was 15% of lighting projects). One-for-one fixture replacements represent the most common retrofit approach, ranging from 60-90% of commercial lighting program savings. The majority of installed products are linear LED tubes, but the share of LED fixtures is reportedly increasing.

Lighting programs are largely driven by prescriptive rebates on light fixtures. Prescriptive rebates for controls are also offered in some areas but have much lower uptake. Programs do not offer prescriptive incentives for task tuning, although Xcel Energy's incentive for networked lighting controls requires that high end trim be set at 80% or lower. One program manager noted that task tuning could be addressed through a custom incentive approach. Most rebate activity is served through downstream programs, with only one utility reporting an upstream pathway for commercial lighting incentives. Support for lighting redesign (large customers only) is offered by one utility but the approach has been de-emphasized in recent years as prescriptive LED incentives have been generating good results and they shifted focus toward diversifying savings through non-lighting projects.

Programs do not encounter significant barriers on LED retrofit projects. Paybacks are favorable and while capital constraints may cause temporary delays, they do not often prevent lighting projects from being done. Several utilities mentioned that they still see LEDs replacing T12s, though T8s are more often the equipment being replaced. The typical age of lighting being replaced is 10-15 years. Measurement of light levels is not done for most lighting retrofits. When it is done, it is more often to ensure the post-retrofit illuminance is at least the same or greater than pre-retrofit levels. Assessment of light levels is more common in warehouses, manufacturing, K-12 schools and universities. It is also more common on gut renovation and new construction projects. Delamping is a component of some LED retrofit projects and a couple of interviewees noted that their programs can take delamping into account when calculating incentive amounts.

Lighting controls face greater barriers to uptake and most programs have not seen robust participation to date. Low customer and contractor awareness are often barriers for adoption of lighting controls. Particularly in rural areas, there are fewer companies with lighting design expertise serving the market. Electrical contractors are often looking for fast wins and less likely to push projects that involve more complexity. In addition, there is a lack of standardization across controls products. Each manufacturer has its own approach and there is a necessary time investment to understand the differences in installation, setup and programming. There is also a perception that the LEDs are addressing a customer's energy efficiency goals and that pursuing controls for a relatively small amount of additional savings is not worth the effort.

While LED retrofit opportunities remain strong in the near term, several program managers cited concerns about longer-term impacts when savings from LED lighting decline due to more stringent code baselines and market penetration of LEDs approaches saturation. Program managers are looking for new ways to promote deeper customer engagement in energy efficiency, moving away from one-time transactional participation and toward a sustained journey of engagement over time.

Interviewees were mixed about whether programs should play a role in assessing and optimizing light levels. Some felt it was a "policing" function they do not want to perform. One utility noted it is a service they provide if customers ask for it. Most interviewees noted that light level optimization could be a viable future strategy if the economics are good from a customer and program standpoint. Smaller utilities expressed concerns about having adequate resources to deliver this kind of program offering. Others felt it would be more viable in specific building types like schools and offices, and less viable in others like retail. Wireless controls could make light level optimization strategies a lot easier to pursue when prices decrease over time. Light level optimization could be a way to get deeper customer engagement, but program managers noted the following challenges must be understood and addressed.

- The customer decision process is different for lighting control projects than lighting retrofits, and there are more stakeholders involved.
- Light level optimization involves a more complex set of occupant preferences, particularly when people in the same space have different preferences.
- Lighting systems with advanced controls are more costly and take more time to commission, particularly when occupant feedback is considered and addressed.
- Marketing light level optimization to customers who have completed a recent lighting retrofit must employ careful messaging. Need to avoid the implication that the customer is getting less value from the original LED retrofit than expected.

Stakeholder Interviews

We interviewed staff from ten businesses with varying roles in lighting projects in the Midwest. These businesses included lighting and lighting controls manufacturers, an energy efficiency consultant, an electrical contractor offering lighting retrofit design services with an emphasis on energy efficiency, manufacturer sales representatives offering some level of design services, and distributors also offering some level of design services.

These companies serve a diverse group of building types, but customers primarily fall into the commercial office, healthcare and education categories. Industrial facilities are also an important sector for lighting retrofit opportunities. Most stakeholders indicated most of their lighting projects are one-to-one fixture replacements in existing spaces, but they are seeing increasing customer interest in going further with enhanced controls and light level optimization, especially among larger customers. Customers in smaller lighting retrofit projects tend to pursue one-to-one fixture replacement with little interest in going beyond code compliant controls. The stakeholders who deal more with major renovations or new construction projects typically have more opportunity to explore controls capable of task tuning, even if the capability is ultimately under-utilized. Several try to influence client decisions, especially in retrofit projects, and try to steer them to more efficient solutions.

The major lighting manufacturers have products with task tuning capabilities. As compared to code-required controls, the incremental cost of purchasing LED fixtures capable of dimming is small to none. There is additional cost involved in connecting the fixtures to lighting control systems that deploy the dimming commands. These systems can range from simple systems with basic occupancy and daylighting functionality to systems capable of advanced lighting controls, including task tuning. There are additional costs for the contractor’s time to wire basic low voltage lighting controls or to program a wireless system with advanced control functionality. However, contractors lack of familiarity with programming requirements of advanced wireless systems often leads to costs one- to two-times more expensive than a basic low-voltage wired system. As contractor familiarity with these systems increases and manufacturers continue making them more plug-and-play, these costs will continue to decrease.

In order to support light level optimization on projects, designers need to understand which control products have these capabilities and include them in their design specifications. Manufacturers' often have draft specification language that can be used as a starting point. However, these specifications tend to focus on equipment requirements and less on how to optimize light levels once the products are installed. One stakeholder suggested execution requirements calling for field-verification of specified light levels. Specified light levels should include guidance on where illuminance values should be measured. The intent being lighting control setup and programing, including task tuning, with verification and documentation of pre- and post- light levels along with final control system inputs. Specifications can be written to include submittal of this documentation prior to any functional performance testing or final project inspections.

There is a general sense that customers are reluctant to install and deploy lighting controls because they do not have a clear understanding of potential benefits. For example, many customers believe that LEDs deliver all the energy savings needed on a given project. Additional energy savings from controls are often perceived as small and not worth the additional cost and complexity. When controls are implemented on a project, the decision is often based on other benefits, such as space usage flexibility or occupant comfort, with energy savings being a nice additional bonus.

Generally, the companies we interviewed see over-lighting as an issue. They generally indicated that the conversion to LED lighting fixtures creates over-lit spaces that could be task tuned to 75-80% of the designed light level. Several cited experience working on projects that achieved even higher levels of task tuning.

But interviewees also noted that light levels are highly subjective—individuals have different brightness preferences. LEDs provide light more evenly throughout the space as compared to the fixtures they are replacing. This plays into this perception of brightness, as the same measured illuminance is often perceived as brighter by occupants. So, getting occupant feedback on light levels and buy-in on the task tuning strategy can be even more important than simply taking light meter measurements and ensuring the recommended level of illuminance.

Besides capital cost, the following other barriers were identified for implementing systems capable of task tuning:

- More complex systems to install, commission and operate.
- Contractor and end user education on the benefits of controls and light level optimization.
- Varied personal preferences for light levels.
- Security concerns related to connecting a potentially unsecured system to the building's network.

Trade ally and end user education is critical to ensuring adoption of task tuning. It can take significant time to educate someone on the benefits of controls and how to deploy them correctly. But once understanding is achieved, they often will begin implementing it on subsequent lighting retrofit projects. Targeting these kinds of educational investments on larger building or portfolio owners may be an effective strategy for achieving replication and scale, in addition to educating electrical contractors, distributors, and other influential market actors.

A few companies reported that they consider light levels in about 75% of their retrofit and new construction lighting projects. They indicated that they set minimum illuminance targets to code or IES requirements. They use photometric calculations to hit the target and to advise their clients on the possibility of reducing fixture count while maintaining or improving lighting performance. However, photometric calculations are often done with little to no knowledge of the furniture and finishes that will be used in the space. Under this circumstance, the photometric modelers will often use conservative assumptions to reduce the chance of underlighting a space. Improving photometric modeling accuracy would require more coordination with architect and interior designers, which entails more time and higher budgets.

There is little to no follow-up measurement of light levels in these spaces once the new lighting is installed. However, light levels measurements are sometimes taken in existing spaces to gauge the pre-retrofit light levels. This information is then used as a starting point for establishing a design target for the retrofit.

Other lighting metrics used by the companies we interviewed include: illuminance uniformity ratios; evaluation of contrasts and shielding of light sources to reduce glare; color rendering index; and WELL Building standards. This range of metrics illustrates that although light levels are important, they are not the only criteria for success, and may not be the main priority of a retrofit.

Interviewees cited the following as trusted sources of lighting information:

- Illuminating Engineering Society, including Lightfair
- National Association of Lighting Management Companies
- Lighting manufacturers and distributors

Most of these companies are aware of utility programs in Minnesota that provide incentives for energy efficient lighting. They would like to see these programs do more to encourage light level optimization and advanced controls, including revisiting previous retrofit projects to further optimize light levels. Some would like a prescriptive offering to avoid the increased complexity of custom calculations. Others mentioned engaging lighting designers for delivery of lighting optimization services since electrical contractors typically focus on installing products, not light level design. Other programmatic suggestions made by interviewees included:

- Provide rebates for distributed digital controls (rather than just occupancy or photosensors sensors).
- Provide rebates for manual dimmers.
- Move away from fixture-based incentives in favor of per square foot.
- Expand the number of upstream programs that simplify participation and allow for manufacturers and distributors to pass along rebates to customers.
- Once established, keep program offerings similar over time.

- Determine a set of required contractor certifications for program participation.
- Collaborate more with lighting designers on determining appropriate light levels.

Conclusions and Recommendations

There is growing potential in Minnesota to capture energy savings from lighting optimization and advanced lighting control strategies. LEDs are gaining market share for a range of interior applications. Even when dimmable lighting systems are installed, tuning the system is not standard practice and our research shows that many spaces are over lit as a result. The primary functionality needed for task tuning is having the ability to reduce light levels within the lighting system's controls. This type of control first became available with dimming ballasts for fluorescent fixtures, mostly utilized in conjunction with photosensor controls. LEDs are inherently dimmable and quickly gaining market share in Minnesota. However, not all LED systems also include the control needed to adjust light levels. Best practice is to include these controls, which are incrementally inexpensive, in LED retrofit and new construction applications. The Conclusions and Recommendations section discusses energy efficiency program strategies that support optimization of light levels in commercial buildings, cost-effectiveness of task tuning projects, and lessons learned from task tuning projects we have implemented.

Program Strategies to Optimize Light Levels

A range of energy efficiency program strategies can be deployed to promote optimized light levels in commercial buildings, from enhancements to existing prescriptive lighting programs to new stand-alone initiatives. In the program interviews we conducted four of six Minnesota program managers expressed interest in investigating the viability of light level optimization as a future program strategy. Four expressed interest in advanced lighting control strategies and one is already administering program offerings for NLC. Program managers cited ensuring the long-term viability of commercial lighting programs as a key motivator for pursuing these approaches. One interviewee noted that light level optimization could be a strategy for forging deeper engagement with customers around building energy performance.

Table 22 summarizes a range of program strategies that can be used to optimize light levels in commercial buildings.

Table 22: Program approaches for light level optimization.

Strategy	Description	Incentive Approaches
Prescriptive lighting program enhancements	Higher incentives for dimmable fixtures	\$/unit
	De-lamping incentives	\$/unit
	Incentive bonus for including task tuning in the lighting retrofit project scope	\$/ft^2

Strategy	Description	Incentive Approaches
Task tuning of previously-installed dimmable LED lighting	Incorporate measurement of light levels and task tuning into RCx program scope	$/kWh
	Stand-alone initiative to revisit buildings that have installed dimmable LEDs + controls; measure light levels and tune to IES recommendations	$/ ft^2
Advanced lighting incentives	Incentives for installation of NLC, LLLC, design assistance, commissioning	$/ft^2 $/unit $/kWh

Prescriptive lighting programs are prevalent and there is lots of opportunity for deploying strategies that promote optimization of light levels. In the Minnesota program interviews we conducted, TLEDs (which are not dimmable) represent a significant share of the rebate activity. Our site visits found that illuminance for spaces lit by whole fixture LEDs was lower than those lit by TLEDs. It is already common program practice to offer a higher incentive for dimmable fixtures as compared with linear tubes. Incentives for reducing the number of installed light fixtures or tubes (delamping) is a way to reduce light levels with non-dimmable fixtures. Several Minnesota program interviewees mentioned support for delamping through their existing commercial lighting programs. A program can also provide guidance to help customers select the right lumen package when they purchase non-dimmable fixtures. Best practice is to use photometric modeling to identify the lumen package for a fixture selection that provides the recommended illuminance for a given space. Several manufacturers provide controls hardware that can be layered onto existing dimmable LEDs to enable more advanced control strategies like task tuning, and these products can be incentivized. Prescriptive lighting programs can also offer incentive bonuses for customers that install dimmable fixtures and demonstrate that task tuning has been completed. The *Verification* section below includes a summary of high level and in-depth approaches to verifying task tuning. Although task tuning can be implemented separately from a lighting retrofit, it is more cost-effective to optimize light levels at the time of the lighting retrofit because the number of required site visits is reduced.

This study demonstrates that there is energy savings opportunity from implementing task tuning in facilities that have already installed dimmable LED lighting and the necessary controls. This savings potential can be captured by incorporating light level optimization into the scope of an existing program like RCx, which involves a comprehensive assessment of a customer's facility to identify and implement energy savings opportunities through optimization of lighting and HVAC controls. Utilities can also offer a stand-alone program that supports task tuning. More information on this approach can be found in the *Program Elements* section below.

In the last five years, utilities across the country have begun deploying incentives for advanced lighting technologies like NLC and LLLC. NLC refers to an intelligent network of luminaires and controls which are programmable through a software interface and have the capability to provide monitoring data on system performance. LLLC is a subset of NLC in which each luminaire contains occupancy and photocell sensors, a continuous dimming ballast/driver and a luminaire controller, allowing for deployment of lighting control strategies at a granular level. In Minnesota, Xcel Energy offers incentives for NLC systems that meet the following requirements: (1) product listed on DesignLights Consortium qualified product list for NLC; (2) high end trim at 80% or less; (3) daylight responsive controls as specified in International Energy Conservation Code 2015; (4) occupancy/vacancy controls with timeout set to 20 minutes or less; and (5) system has been properly commissioned. Many programs offer per-kW or per-kWh incentives based on custom calculations, although programs administered by Focus on Energy[30] and AEP Ohio[31] offer NLC incentives on a per-square foot basis.

Program Elements

The following sections talk about program approaches that support optimization of light levels in commercial buildings. These approaches could be incorporated as elements of existing programs or could provide the foundation of a stand-alone program targeting task tuning opportunities.

Outreach

Implementing task tuning requires the lights to be dimmable. Whether you are administering a task tuning program or targeting task tuning opportunities through RCx or another program, you need to be able to efficiently target buildings with dimmable lights. In general, this includes all buildings that have LED fixtures and/or daylighting controls (i.e. plenty of perimeter zones). Potential candidates for task tuning include:

- **Office**: Ideal targets have large open offices with high controlled power or many private offices in which you can apply the same tuning approach quickly by copying control settings.
- **Education**: Ideal targets have many similar classrooms in which you can apply the same tuning approach quickly by copying control settings.
- **Institutional**: Libraries and higher education campuses are great candidates for lighting optimization approaches. Program personnel could potentially train a small number of facility staff who could then apply tuning across a portfolio of buildings.
- **Big Box Retail**: Combining high lighting powers with increasing penetration of highbay LEDs means that there is significant energy savings potential from task tuning in retail. Programs will face obstacles in convincing owners to reduce light levels, as they often view this as potentially reducing product sales. However, there is a trend in retail lighting design towards lower ambient

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[30] Focus on Energy Networked Lighting Controls fact sheet. Accessed June 1, 2020. Available at: https://focusonenergy.com/sites/default/files/Application_PDFs/Networked_Lighting_Controls.pdf

[31] AEP Ohio Networked Lighting Controls fact sheet. Accessed June 1, 2020. Available at: https://www.aepohio.com/global/utilities/lib/docs/save/business/programs/AEPOhio/2019/2019%20Bus%20Fact%20Sheet_NetLight_v2_190109v1.pdf

lighting paired with the use of more accent lighting to highlight the merchandise. As this trend continues, there is likely increasing potential for task tuning in retail applications.

- **Light Manufacturing**: Similar to big box retail, this sector has high lighting powers and increasing penetration of highbay LEDs. However, safety concerns around potentially dangerous manufacturing process may be an obstacle. Coupling task tuning with task lighting may be a way around this barrier.
- **Warehouse**: New code requirements for lighting controls and higher penetrations of highbay LEDS will lead to increasing potential in this sector. Large areas of similarly controlled lights help with cost effectiveness.
- **Parking Garages**: New code requirements for lighting controls in parking garages will lead to increasing potential in this sector. Large areas of similarly controlled lights help with cost effectiveness.

In general, buildings that have had a one-for-one replacement of existing lighting with LEDs may be good candidates for task tuning because most electrical contractors doing these installations are not measuring light levels or ensuring that systems are properly commissioned. Utilities could review past lighting retrofit projects to identify candidates for lighting optimization outreach. They could also engage stakeholders in partnerships to identify and recruit potential projects:

- **Portfolio owners**: property management companies, higher education, government (state, county, city), retail chains.
- **Professional associations**: IES, International Facility Management Association, United States Green Building Council, ASHRAE
- **Trade ally relationships**: electrical contractors, lighting controls manufacturers, design firms

Below are some screening criteria that can be used to prioritize lighting optimization outreach:

- Building size minimum of 25,000 square feet (ft^2)
- High opportunity building type such as office, education or manufacturing
- LED fixture retrofit done in the last 3 years
- Installed dimmable fixtures and controls capable of deploying high end trim

Training

Training is a key component of any initiative aiming to promote measurement and optimization of light levels. Whether the program is seeking to incorporate task tuning training into an existing commercial lighting program or to launch a new task tuning initiative the following topics should be addressed in the training strategy for program staff and trade allies involved in program delivery:

1. ***Fundamentals of Lighting***: This course was developed by the Illumination Engineering Society and covers a range of lighting-specific subjects at an appropriate level for gaining proficiency in

task tuning. The class is offered through local chapters of IES, including the Twin Cities chapter.[32] Participants typically meet one night per week for two and a half hours. The Twin Cities course lasts 10 weeks. Training topics include:

- Basic lighting concepts, vision, and color
- Electric light sources and ballasts
- Luminaires and lighting controls
- Photometry and lighting calculations
- Lighting design process
- Lighting for interiors and exteriors

2. ***Lighting Controls***: The Lighting Controls Association's Education Express[33] offers a variety of lighting control and dimming control classes.

3. ***How to use a light meter***: The documentation that accompanies a specific light meter will provide most of the detail needed to operate the light meter. Proper placement of the light meter is necessary in order to get the most accurate readings. Light meters should be placed on the working surface or tripod when possible, and the person operating the meter should ensure that their body is not blocking any light by stepping away from the meter during the reading. When taking readings while holding the meter, the light meter should be held away from the body as far as possible, and the person should endeavor to position themselves in such a way as to block as little of the light as possible.

4. ***Basics of major manufacturer control systems***: The biggest variable in any task tuning effort is understanding the nuances of the lighting control systems serving a given space. Energy efficiency program staff should work with control system manufacturers to identify training resources covering the basics of their systems.

A targeted program to implement task tuning of existing lighting in commercial buildings would most likely involve training electrical contractors in a protocol of measuring light levels similar to the approach described in *Expedited Assessment* above, as well as the steps for adjusting light levels to the recommended values. The training would ideally also include strategies for occupant engagement and education.

Lastly, Appendix E includes a checklist that could be followed by program staff or trade allies supporting task tuning projects when undertaking task tuning of a given lighting system.

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[32] IES Twin Cities chapter, Local Education Classes. Accessed June 1, 2020. Available at: http://iesmsp.org/local-education-classes/

[33] Lighting Controls Association, Education Express web site. Accessed June 1, 2020. Available at: http://aboutlightingcontrols.org/Education_Express/welcome.php

Occupant Education

Task tuning is essentially a tradeoff between energy consumption of a lighting system and light levels in a space. When performing task tuning, it is important to balance energy savings with occupant visual comfort, as aggressive tuning will result in high energy savings at the expense of occupant satisfaction.

Complicating this balance is the fact that occupants perceive light levels differently both between individuals and under varying situations. When tuning a lighting system some occupants may provide feedback that the tuned light levels are too low while others say they are just right. Additionally, if an occupant is present when the tuning occurs, they may provide immediate feedback that the tuned light levels are too low simply because their eyes were adjusted to the previous, higher light levels. Had the tuning occurred without them present, the lower light levels may have gone unnoticed when the occupant first perceived them upon arrival into the space.

Because of these complexities, there are two general approaches to task tuning with respect to occupants: tuning when occupants are not present (unoccupied periods) or tuning when occupants are present (occupied periods). Task tuning during unoccupied periods occurs with no occupant feedback while tuning during occupied periods solicits occupant feedback either through formal pre/post surveys or informal conversations during tuning. The following tables (Table 23 and Table 24) highlight the pros and cons of each approach. Generally, tuning during unoccupied periods reduces complexity and cost but increases risk of occupant discomfort and complaints. On the other hand, by tuning during occupied periods, occupant discomfort and complaints can be avoided and ultimately may achieve better energy savings results because occupant buy-in to the process improves savings persistence.

Table 23: Pros and cons of tuning during unoccupied periods

Pros	Cons
Without occupant feedback, the tuner can adjust the lights to a level that maximizes energy savings.	Increases risk of occupant visual discomfort and associated complaints.
Minimizes the chance of an occupant providing false feedback based on perceived relatively lower light levels.	May reduce savings persistence as facility managers respond to occupant complaints.
If tuned at night, the tuning process itself is less complicated because there is no daylight to contend with or photosensor controls to adjust.	NA
Reduced complexity means tuning takes less time and is less costly.	NA

Table 24: Pros and cons of tuning during occupied periods.

Pros	Cons
Decreases risk of occupant discomfort and associated complaints.	Occupants may provide inaccurate feedback based on perception.
May increase energy savings if occupants are comfortable with light levels below IES recommendations.	Occupant feedback may result in reduced or no energy savings.
Increases savings persistence, as facility managers will not need to respond to occupant complaints.	If task tuning is implemented during the day, the tuning process itself is more complicated and is best done under lower-light conditions.
NA	Increased complexity means tuning takes more time and is more costly.

We recommend that task tuning be conducted with occupant feedback to achieve a balance between energy savings and occupant visual comfort. However, if obtaining occupant feedback is too complex or costly, special care should be taken to not adversely affect occupant visual comfort. Choosing more conservative light level reductions than IES recommendations is one method for achieving this goal. For instance, if a space was found to have an average illuminance of 60 fc and the IES recommendation for that space type is 30 fc, a conservative reduction would be to reduce the average illuminance to 45 fc. Although this would reduce short-term energy savings, it would increase energy savings persistence as facility managers would be less likely to override tuned controls based on occupant complaints.

Another approach would be to lower light levels incrementally during unoccupied periods over the course of several weeks. For instance, if a space was to be tuned from 60 to 30 fc, a facility manager (or other onsite personnel) could reduce the light levels at night in 5 fc increments over the course of six weeks. In this way, the occupants would acclimate to each new light level, as opposed to having to adjust to the entire reduction at once. If an occupant does complain, the facility manager could simply raise the light levels to the previous increment before the complaint occurred. In this way, occupants could be indirectly polled without survey bias.

There is also the risk that, even though the average tuned illuminance levels meet IES recommendations, a few areas or occupants are still not receiving enough light to perform their tasks. This is particularly prevalent in spaces with widely spaced lighting or tall cubicles or partitions. This situation can be avoided by ensuring that illuminance at the critical workplane is not too low. The critical workplane is defined as the location where an occupant is performing a task that has the lowest light level. Polling the occupant at this location directly is the surest means of determining whether they are comfortable with the lower light levels. If the light levels are too low, the ambient light level may simply be increased, or task lighting may be added at this location. Appendix F includes guidance on how to measure illuminance at the critical workplane.

Incentive Strategy

Programs are currently using a variety of incentive approaches for advanced lighting control strategies including per-fixture bonuses for LLLC, custom incentives on a per-kilowatt (kW) or per-kWh basis, and incentives based on the building area ($\$/ft^2$) impacted by the lighting controls. For a task tuning initiative, a $\$/ft^2$ incentive structure offers several compelling advantages:

- It is a metric that building owners understand and regularly use in the decisions they make regarding their building.
- It more clearly shows the degree to which the incentive offsets project costs and can be readily incorporated into project budgeting.
- It sends a consistent, upfront signal, unlike incentives based on energy savings which cannot be reliably estimated until there is a completed project scope and some initial engineering calculations.

A targeted program for task tuning LEDs after a lighting retrofit could employ $\$/ft^2$ incentive structure. The program could also subsidize a portion or all of the cost of the task tuning site visit. The Cost-Effectiveness section below includes information on costs and savings that can be taken into account in developing an incentive structure to support task tuning.

Verification

We group possible verification approaches into two categories:

- **Level 1:** A high-level check that task tuning has been completed. Could entail a program representative measuring light levels in a representative sample of incentivized buildings or checking that lighting controls have indeed been adjusted from their factory defaults. This approach is less time consuming and less costly but does not quantify actual energy savings.
- **Level 2:** Onsite measurement of energy impacts from task tuning. Effort is similar to the Measurement and Verification process outlined in the International Performance Measurement and Verification Protocol[34] or ASHRAE Guideline 14.[35] This typically entails using power meters or current transducers to measure lighting system energy consumption both before and after the task tuning has occurred. The associated energy savings is then determined by comparing the normalized energy consumption from both periods. This level is more time consuming and costly than the Level 1 approach but quantifies actual energy savings. Could be performed on a representative sample of projects.

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[34] DOE. 2002. *International Performance Measurement and Verification Protocol*. Available at: http://www.nrel.gov/docs/fy02osti/31505.pdf

[35] ASHRAE. 2014. American Society of Heating, Refrigeration and Air Conditioning Engineers. *Standard 105-2014, Standard Methods of Determining, Expressing and Comparing Building Energy Performance and Greenhouse Gas Emissions*. Table J2-D, pg. 23.

As with any energy efficiency program, strategies for ensuring energy savings persistence should be considered. The Minnesota Technical Reference Manual (TRM) states savings from lighting control measures have a useful life of eight years. However, since there is a strong occupant comfort component to task tuning, there is risk that recommended light levels will be overridden after the task tuning intervention, shortening the actual measure lifetime. This risk can be mitigated by involving the building occupants and facility staff in the task tuning process. Getting their feedback as to appropriate light levels is helpful in maximizing energy savings while maintaining a high level of occupant comfort. Further, educating one point of contact—typically the facility manager—on how to use the lighting controls, and why task tuning is important helps with savings longevity.

Cost-effectiveness

The methodology for determining the energy savings associated with task tuning is outlined in the Analysis section of this report. Typical energy and demand savings/ft^2 values are summarized in Table 25.

Table 25: Typical electricity and peak demand savings.

Building Type	**Typical Electricity Savings (kWh/ft^2)**	**Typical Peak Demand Savings (W/ft^2)**
Office	1.03	0.23
Education	0.46	0.13
Manufacturing	0.14	0.03
Warehouse	0.17	0.04

The tasks and associated time for task tuning a LED system are outlined below.

1. ***Preparation (2-4 hours):*** This task includes acquiring and reviewing building drawings, specifications, and lighting control documentation. In addition, time must be spent coordinating the site visit.
2. ***Measurement (6-8 hours):***
    - Site tour
    - Facility staff and occupant interviews
    - Measure pre-tuned light levels
    - Calculate pre-tuned average and critical light level
    - Determine recommended average light level
    - Calculate recommended critical light level
3. **Controls adjustment (2-4 hours)**:

- Determine sequence for adjusting light levels
- Adjust system to recommended working plane light level
- Verify that critical light level meets recommendation

We performed a simple payback analysis to understand the economics of a task tuning project. For the purpose of this analysis we assume that the cost of task tuning is limited to the time involved, and does not include any equipment, maintenance or other costs.

For this analysis, we needed to develop typical utility costs savings and labor costs for task tuning. We therefore assumed that the dimmable lighting system had an average lighting power density and percent savings factor for each space type calculated from the LED-lit spaces that we characterized. We additionally assumed annual operating hours of 4,439 hours for spaces in offices, 3,424 hours for spaces in education facilities, and 4,746 hours for spaces in manufacturing and warehouse facilities.[36] Finally, we used an average electric rate of $0.1028/kWh.[37] Taken together, these assumptions allowed us to calculate the utility cost savings per square foot for each space type.

The time associated with task tuning involves becoming familiar with the lighting control system, measuring average light levels, and adjusting the lighting system to provide recommended light levels. The time requirement varies considerably based on the tuner's level of familiarity with the lighting system. For example, it would take someone who is very familiar with the system (i.e. a lighting manufacturer representative or commissioning agent of a new system) much less time than someone who is not familiar with the system (i.e. an energy service representative trying to tune an existing system).

When estimating the labor costs, we assumed that the lighting system served 25,000 square feet at a labor cost of $88 per hour.[38] Note that labor costs scale with square footage, and that the assumed area of 25,000 square feet serves as a typical project size.

We estimated labor costs under two scenarios: (1) task tuning a new system associated with a new construction or major renovation project and (2) a retrofit scenario that involves visiting a site with previously-installed LED lighting to task tune the system. For new construction or major renovation, we assume that the experienced technician or trade ally would take about 16 hours, since they would already be familiar with the system because they participated in the design and commissioning process. For the retrofit case, more time would be required to understand the system, learn how to adjust its controls, as well as understand the zoning of light fixtures. We therefore assumed that the same experienced technician or trade ally would need twice the time to tune the existing system (32 hours).

Using these assumptions, we calculated simple paybacks as outlined in Table 26.

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[36] "State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs", Version 3.0, pg. 205.

[37] U.S. Energy Information Administration, Electric Power Monthly, January 2020, Table 5.6.A. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

[38] RSMeans Electrical Cost Data 2016; with inflation rates of 2.1%, 1.9% and 2.3% for 2017, 2018 and 2019, respectively

Table 26: Cost savings and simple paybacks for task tuning LED systems.

Space Type	Cost Savings ($/ft^2)	Simple Payback (yr) New Construction	Simple Payback (yr) Existing
Office	$0.121	0.5	0.9
Conference	$0.090	0.6	1.3
Warehouse	$0.005	10.7	21.4
Corridor	$0.177	0.3	0.6
Classroom	$0.036	1.6	3.1

With the exception of warehouse spaces, the cost savings and associated simple payback of task tuning LED systems are very good. Operating cost savings from reduced energy use are between $0.036 and $0.177 per square foot, resulting in a simple payback of between 0.3 and 1.6 years for new construction and between 0.6 and 3.1 years for existing system retrofits. For warehouses, the lower savings potential from lower lighting power and task tuning lead to long simple paybacks. **Due to these short payback periods, we recommend that task tuning be implemented in new construction projects or major renovations in which a dimming system is already planned as part of the design requirements. For the same reason, if a dimming-capable system already exists in a facility, task tuning should be strongly considered to achieve cost-effective energy savings.** Although task tuning does not stand alone as a reason to purchase a dimming system, task tuning would help justify the installation of a more complex lighting control system than originally planned, or prevent a dimming system that is part of a lighting design from being value engineered out of the budget.

For comparison, we conducted a similar payback analysis of other types of commercial lighting efficiency projects: TLED retrofit (B-type), LED fixture installation, and NLC retrofits. Note that we selected TLED Type B since it supports dimmability and task tuning. Type A TLED retrofits would likely result in shorter paybacks, but without the task tuning capabilities. Cost savings components include reduction in energy use, reduced maintenance from bulb and ballast replacement, and lower maintenance requirements for LEDs. Incentive rates are based on typical per-fixture and per- ft^2 incentives offered by Midwestern lighting programs. Table 27 presents results from this payback analysis.

Table 27: Simple paybacks for other commercial lighting projects.

Description	TLED-B	LED fixture	NLC low	NLC high
Installation cost ($/ft^2)	$1.16	$2.78	$3.41	$5.46
Incentive ($/ft^2)	$0.12	$0.17	$0.21	$0.21
Cost savings ($/ft^2)	$0.35	$0.38	$0.46	$0.46
Simple payback (yr)	3.6	7.7	7.6	12.5

To assess program-level cost-effectiveness for task tuning, we ran two scenarios: (1) a stand-alone task tuning retrofit program serving 25 projects per year with an average size of 25,000 square feet; and (2) a similar program serving 50 projects per year with average size of 50,000 square feet. Both programs subsidize the cost of task tuning at 75%. Both programs offer an incentive of $0.03 per square foot of tuned space. Tuning achieves gross annual savings of 0.66 kWh per square foot. Program implementation costs that are relatively fixed regardless of participation include management, administration, marketing, outreach and contractor training, estimated at $150,000. Results are presented in Table 28.

Table 28: Task tuning program cost scenarios.

Cost	Scenario 1	Scenario 2
Customer incentives	$18,750	$75,000
Task tuning subsidy	$52,800	$105,600
Program implementation	$150,000	$150,000
Total budget	**$221,550**	**$330,600**
Annual electric savings (kWh)	412,500	1,650,000
Incentive cost ($/kWh)	$0.05	$0.05
Non-incentive cost ($/kWh)	$0.49	$0.15
Total cost ($/kWh)	**$0.54**	**$0.20**

Serving larger buildings increases the viability and cost-effectiveness of task tuning programs. Programs can employ targeting strategies to boost cost-effectiveness. The most cost-effective task tuning projects involve buildings with large areas of similarly controlled lighting, such as large open offices or many classrooms for which the same level of tuning could quickly be applied. Regardless of the building, it is likely not cost-effective to measure the light levels in all spaces. Rather, a sample of representative spaces should be identified and measured, preferably using one of the expedited assessment approaches outlined in the Expedited Assessment section. The resulting lighting level reduction can then be applied to all similar spaces. Additionally, networked lighting systems that come with an online programming interface can be tuned quickly, even allowing tuning to occur through a simple, remote programming interface after measurement occurs. Task tuning is more time-consuming in non-networked systems because the changes must be made on-site via adjustments at each control device. It is also more cost-effective to deploy task tuning at the time of the lighting retrofit instead of coming back to implement task tuning on a subsequent visit. There is a high fixed cost in merely getting into the building, understanding the space types and associated lighting controls. If task tuning is part of the retrofit process, the time associated with tuning the lights is relatively short.

Lessons Learned

Slipstream has conducted light level investigations in Minnesota, Wisconsin and Michigan. Table 29 outlines lessons learned throughout relevant past projects. Programs that seek to address task tuning in a targeted way can benefit from incorporating these lessons into their planned approach.

Table 29. Lessons learned from implementing task tuning.

Topic	Issue	Lesson
Useful light and lumen output	Delivered light (illuminance) is a better metric for evaluating LEDs than lumen output since it discounts wasted light. LEDs waste less light than their conventional counterparts.	Evaluating LEDs primarily based on lumen output can underestimate or distort its performance and suitability for a given application. Lighting designers may be inclined to over light spaces when specifying LEDs leading to greater opportunities for task tuning.
Scenes	Lighting controls can be used to lower light levels to preset levels such as audiovisual mode in classrooms or conference rooms. These settings affect the amount of savings from task tuning.	Account for scene control in determining the amount of savings from task tuning. Potentially by only assuming hours when lights are on full, and not in audiovisual mode.

Topic	Issue	Lesson
Getting accurate readings	Several conditions make it difficult to get accurate light level readings, e.g., spaces with a lot of daylight.	Never take illuminance readings in direct sunlight. Lower blinds or take illuminance measurements away from windows. Let lights warm up before taking measurements. Light output can change over several minutes. Use a light meter, current transducer, or power meter to know when a system has equilibrated.
Tuning daylit spaces	More complicated than tuning non-daylit spaces.	Do not be too aggressive with tuning (i.e. reducing light levels below IES recommendations). While there may be ample light during most occupied hours, this may not be the case during periods of dawn and dusk.
Occupant satisfaction	While IES has established light levels for various tasks, individual needs vary. Tuning all ambient lighting does not account for individual preferences.	Add task lighting to enhance individual control. This strategy allows for energy savings from task tuning, while satisfying the few individuals whose visual needs are not met by this strategy.
Retrofit applications	While LED market share is growing rapidly, there are also opportunities to add dimming and photosensor controls in retrofit applications. This will increase the energy savings potential for task tuning over time.	It is essential to properly pair dimming and controls with LED retrofits, otherwise task tuning opportunities are limited.
Establishing light levels	It is difficult to determine a light level target.	The IES *Lighting Handbook* publishes exhaustive tables of appropriate light levels by space type and task. For new construction, design intent may also be used. For existing buildings, similar spaces in the same building

Topic	Issue	Lesson
		or another of the owner's facilities may also be used.
Value of commissioning	The benefits of commissioning are not always clear to building owners, and perceptions about cost and complexity present challenges for proper commissioning.	Commissioning ensures that light levels are correct and catches other problems such as poor placement of photosensors or other issues with daylighting controls.
Common misconceptions	Perception that LEDs have enough savings without controls, and that adding controls is prohibitively expensive	Highlight the non-energy benefits of improved occupant satisfaction and system flexibility of adding control to LED retrofits.
Lack of standardization	Lighting control systems not intuitive and differ by brand – steep learning curve just to figure them out	Leverage manufacturer-provided training and informational resources to get trade allies familiar with a range of products.

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Appendix A: Literature Review

We conducted both a literature review of studies focused on light levels and associated controls to discern the applicability of those studies to the Minnesota market and reviewed best practices of other utility advanced lighting programs.

Literature Review

We conducted a literature search to establish a foundation for our light level analysis project. There is an abundance of information on how to measure light levels and recommendations for light levels for given tasks. There is also a growing body of work measuring energy savings from lighting controls. However, we found little that documents and establishes a baseline of existing light levels in workspaces. This is particularly true for LED-lit spaces, with most of the studies documenting user preferences under more traditional lighting systems.

A common theme among the reports we reviewed was the range of individual preference for light levels. Several studies recorded individual lighting preferences ranging from as low as 8 fc to as high as 148 fc. And, if given the opportunity, different people will choose different illuminance levels even for the same task. This is an indication that any program should include occupant preferences as much as possible when adjusting light levels. The literature also showed that occupants tended to prefer having the ability to control/adjust their own light levels. When given this controllability, they tended to reduce their light levels on average and express higher levels of satisfaction with their lighting systems. Documenting light levels in Minnesota buildings, and the extent to which spaces are over- or under-lit (compared to IES suggested levels) will lead to recommendations for program strategies that allow occupants to control their individual lighting while reducing overhead light levels to reduce energy use.

Following are a few reports and papers that present information on light levels and occupant satisfaction.

Evaluating Tunable Lighting in Classrooms: Trial LED lighting systems in three classrooms in the Folsom Cordova Unified School District. Safranek, Sarah and Robert Davis. 2018.

The Sacramento Municipal Utility District with participation from the Pacific Northwest National Laboratory explored the benefits of tunable-white lighting systems for children with autism spectrum disorder. This report presents results on the energy and photometric performance of the tunable LED system.

Lighting preference profiles of users in an open office environment. Despenic, Marija et al. 2017. Building and Environment, vol. 116.

The authors propose a method for modelling lighting preference profiles based on users control behavior. These profiles can be used to address lighting issues in multi-user, open-space environments.

Sensor-driven, human-in-the-loop lighting control. Tan, F. et al. 2017. Lighting Research and Technology, vol. 50.

Researchers tested a system that incorporated user feedback and occupancy and light sensor data to adjust lighting to changing occupancy and daylight conditions in an office test bed.

Evaluation of an LED Retrofit Project at Princeton University's Carl Icahn Laboratory. Davis, Robert et al. 2015. U.S. Department of Energy, Commercial Building Integration Program.

To prepare for Princeton's first building-wide interior LED project, facility engineers installed multiple samples of several lighting retrofit products and collected feedback from stakeholders on the appearance, perceived impacts on light levels and distribution, and potential glare. This process was used to determine which retrofit product to use.

Lighting and the Living Lab: Testing Innovative Lighting Control Systems in the Workplace. Cordell, David et al. 2014. Perkins + Will Research Journal, vol. 06.01.

This research studied the role of smart lighting strategies and the use of lighting control systems in an office environment. They studied task tuning, variable load shedding and daylight harvesting. Each strategy was tested sequentially for twelve consecutive weeks to determine the ability of each approach to reduce the overall energy consumption, while incurring minimal consequences on productivity and comfort.

Lighting quality perceived in offices. Zumtobel Research. 2014. Fraunhofer Institute for Industrial Engineering, Stuttgart, Germany.

The aim of this user study initiated by Zumtobel and implemented in cooperation with Fraunhofer IAO, was to describe the lighting situation in offices and to record the specific needs of various user groups in different work scenarios. An interactive component of the study allowed participants to choose illuminance levels to suit their needs: more than 60 percent chose levels of 800 lux (80 fc) or higher.

Advanced Lighting Control System (ALCS) in an Office Building. Beresini, Jeff. 2013. Pacific Gas and Electric Company's Emerging Technologies Program.

This report summarizes an assessment project that studied the performance of an advanced lighting control system (ALCS) in a generic office setting. After relamping, reballasting, and adding wireless controls to the existing lighting fixtures, baseline measurements were taken. An initial energy savings of 26% resulted from the implementation of task tuning through the ALCS. A further energy savings of 44% resulted from the implementation of complete ALCS functionality, based on the results of the test at the Contra Costa County Office of Education ending in January 2013.

Light environment in Japanese office buildings after the 3.11 earthquake - field measurements on illuminance levels and occupants' satisfaction. Yoshizawa, N. et al. 2012. International Society of Indoor Air Quality and Climate Healthy Building Conference, Brisbane, Australia.

This study collected and analyzed basic data on light environments in Japanese office buildings after the March 2011 earthquake. Results from field measurements at 14 buildings suggest that workplace dissatisfaction decreases as desktop illuminance increases to approximately 400 lux (40 fc) is reached: the dissatisfaction rate remains nearly constant above this illuminance level.

Personalized dynamic design of networked lighting for energy-efficiency in open-plan offices. Wen, Yao-Jung and Alice Agogino. 2011. Energy and Buildings, vol. 43.

Results from a study on lighting optimization that incorporated task light tuning provided occupants with light levels needed and showed energy savings from both tuning light levels and keeping unoccupied areas unlit or minimally lit.

A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings. Williams, Alison et al. 2011. Lawrence Berkeley National Laboratory.

The authors conducted a meta study of available research on the energy savings associated with lighting controls. In total, they summarize 88 papers, comprising 240 savings estimates of 4 controls strategies; daylighting, occupancy sensors, personal tuning and institutional tuning. Institutional tuning involves adjusting light levels through commissioning and technology but also includes providing control options for building areas or groups of occupants. Personal tuning is defined as an individual adjusting their own light levels to their personal preference using dimmers, wireless on/off switches, bi-level switches, computer-based controls or pre-set scene selection. On average, the lighting energy savings were 36 percent for institutional tuning and 31 percent for personal tuning.

High Efficiency Office: Low Ambient/ Task Lighting Pilot Project. Howlett, Owen. 2009. Heschong Mahone Group (now TRC). Pacific Gas and Electric Company's Emerging Technologies Program.

This report presents the results of a study on the design, installation and monitoring of "low ambient / task lighting" in a small office building in Davis, CA. The project was designed to determine whether light levels could be significantly reduced to save energy, while preserving a comfortable and attractive office environment.

Individual control of electric lighting in a daylit space. Newsham, G. R. et al. 2007. Lighting Research and Technology, vol. 40.

Participants in a daylit office laboratory were prompted every 30 minutes to use dimming controls to choose their preferred light levels. On average, the manual dimming control in this test reduced energy for lighting by 25% compared to a fixed system that provided 500 lx (50 fc) to the desktop.

Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. Galasiu, A. and J. Veitch. 2006. Energy and Buildings, vol. 38.

A review of the literature on occupants' needs and lighting preferences in daylit spaces shows a strong preference for daylight but a wide difference in preferred illuminance levels. The review does suggest that occupants will choose lower electric light levels when daylight is available.

Lighting Quality and Office Work: A Field Simulation Study. Boyce, Peter et al. 2003. Pacific Northwest National Laboratory.

Two experiments were conducted in an office setting designed as an open plan workplace for nine people. The simulated workplace had perimeter windows for views but limited daylight penetration. The two experiments tested different lighting installations to study how office lighting affects the performance of office work and the health and well-being of employees.

Long-term patterns of use of occupant controlled office lighting. Moore, T. et al. 2003. Lighting Research and Technology Journal 35-1.

Daily and seasonal patterns of use were studied in four office buildings where occupants could vary the light level in their working areas. Monitoring of switching behavior revealed that most occupants did nothing more than switch the lights on when they arrived at work. The researchers found some evidence of light levels changed based on daylight availability but little evidence of consistent user preferences for electric light levels.

Lighting programs

Many energy efficiency programs now offer incentives for advanced lighting controls, in addition to incentives for fixture replacements or lighting redesign. These programs typically incentivize adding advanced controls when upgrading to energy efficient fixtures.

Program Administrator	**Brief Program Description**
Xcel Energy – Minnesota	Lighting Efficiency Program. In addition to incentives for upgrading lighting systems, Xcel provides incentives for advanced lighting controls on newly installed networked systems controlling LED lighting technology. Rebates are based on the amount of watts controlled by the system.
Focus on Energy	Comprehensive Lighting Initiative. This program provides incentives for upgrading to energy efficient fixtures, new LED technology and accompanying controls.
Focus on Energy	Networked Lighting Controls *(NLC).* This program requires pre-approval and offers incentives for installing and/or upgrading space with a Design Lights Consortium listed networked lighting control system.
Focus on Energy	New Construction Lighting Power Density Reduction. This program offers incentives for reducing LPD 20%, 30% or 40% below code requirements in new construction.

Program Administrator	**Brief Program Description**
ComEd – Illinois	Networked Indoor and Outdoor Lighting. ComEd offers two options for networked systems: 1) new LED fixture and new lighting controls or 2) new control system on fixtures that don't meet option 1 specs. Option 1 incentive is based on watts reduced and watts controlled; option 2 is based on kWh saved above baseline.
AEP Ohio	Networked Lighting Controls Program. Provides cash incentives on a per square foot basis for upgrading to LED lighting systems combined with networked lighting controls.
Consumers Energy	Business lighting program. Provides incentives for advanced lighting controls as one component of their efficient lighting program. Also offers incentives for new construction projects for reducing Lighting Power Density.
Lighting Technology Energy Solutions (LiTES)	NextEnergy partnered with the Department of Energy, IBEW, DTE Energy and Consumers Energy to launch this program in 2017. This recently completed three-year initiative trained contractors about the latest networked lighting control solutions and helped small to medium-sized businesses deploy networked lighting controls and other advanced lighting strategies.
Baltimore Gas and Electric	Lighting Controls. BG&E offers incentives for networked lighting controls as one component of their lighting efficiency program.
EVERSOURCE: Mass Save, National Grid; Columbia Gas of MA; Berkshire Gas; Liberty Utilities; Unitil	Performance Lighting Program. Supports optimization in new construction and major renovations. Tiered incentives for LPD at least 20% below energy code, as well as luminaire-level lighting controls and networked lighting controls. Includes design assistance incentives for lighting design teams.

Appendix B: Screening Survey

Introduction

Q1 Hello, my name is [INTERVIEWER NAME] and I am calling on behalf of Slipstream, a non-profit research organization. We are conducting research on light levels in Minnesota buildings for the Minnesota Department of Commerce, Energy Resources. Please help us by answering a few questions about lighting in your building. This survey will take about 5 minutes to complete.

[INTERVIEWER NOTE: If respondent wants more information]

This is a research project designed to help the Minnesota Department of Commerce and Minnesota utilities develop energy efficiency programs for commercial lighting.

Q2 First, is your organization's building located in Minnesota?

○ Yes

○ No

Skip To: End of Survey If Is your organization's building located in Minnesota? = No

Q3 Are you knowledgeable about the lighting systems serving this building?

○ Yes

○ No

Skip To: Q5 If Are you knowledgeable about the lighting systems serving this building? = Yes

Q4 Is there someone else in your organization who could answer our questions on lighting in your building?

[INTERVIEWER: ask to be forwarded to that person and/or capture contact information and add to call list. If forwarded repeat introduction (Q1) and then skip to Q5]

Q5 What lighting type serves the majority of your business? [SELECT ONLY ONE]

○ Fluorescent

○ Compact fluorescent

○ Incandescent

○ Halogen

○ High-intensity discharge (HID)

○ Light-emitting diode (LED)

○ Other ____

○ Don't know

Skip Out of Survey if Light-emitting diode is NOT selected…

Q6 Thinking about the whole building in which your business is located, what is the space primarily used for?
[INTERVIEWER NOTE: DO NOT READ. CONFIRM IF NEEDED.] [IF NEEDED: What use type takes up the most space?] [INTERVIEWER NOTE: DO NOT READ, BUT CODE RESPONSES BASED ON DESCRIPTIONS BELOW.]

Key	Building Type	Description	May Include	Does Not Include
1.	MANUFACTURING	Buildings where mechanical or chemical transformations of materials or substances into new products are performed. This includes the assembly of component parts or the blending of materials.	• plants • factories • mills	NA

Key	Building Type	Description	May Include	Does Not Include
2.	EDUCATION	Buildings used for academic or technical classroom instruction, such as elementary, middle, or high schools, and classroom buildings on college or university campuses.	• elementary or middle school • high school • college or university • preschool or daycare • adult education • career or vocational training • religious education	• Buildings on education campuses for which the main use is not classroom. For example, administration buildings, dormitories and libraries.

Key	Building Type	Description	May Include	Does Not Include
3.	OFFICE	Buildings used for general office space, professional office, or administrative offices.	• administrative or professional office • government office • mixed-use office • bank or other financial institution • medical office (see the next column) • sales office • contractor's office (e.g., construction, plumbing, HVAC) • non-profit or social services • city hall or city center • religious office • call center	• Medical offices that use any type of diagnostic medical equipment. These would be categorized under Outpatient Healthcare

Key	Building Type	Description	May Include	Does Not Include
4.	WAREHOUSE AND STORAGE	Buildings used to store goods, manufactured products, merchandise, raw materials, or personal belongings (such as self-storage).	• refrigerated warehouse • non-refrigerated warehouse • distribution or shipping center	NA
5.	other	*Space for additional comments*	*Space for additional comments*	*Space for additional comments*
6.	don't KNOW	*Space for additional comments*	*Space for additional comments*	*Space for additional comments*

Skip Out of Survey If Building Type Is OTHER or DON'T KNOW

Skip to Q7 If Building Type Is EDUCATION, OFFICE, or WAREHOUSE AND Storage

Q6A Does this Manufacturing facility have an associated warehouse space?

○ Yes

○ No

Skip Out of Survey If Manufacturing building has no associated warehouse space

Q7 What is the approximate square footage of the occupied space in this building? If there are multiple tenants, we are looking for the amount of occupied space of the entire building.

○ Record square footage ____

○ Don't know

Skip To: Q9 If What is the approximate square footage of the occupied space in this building? If there are multi...(Record square footage) Is Not Empty

Q8 Would you say that the occupied space of this building is...

○ Less than 1,000 square feet

○ Between 1,001 and 5,000 square feet

○ Between 5,001 and 10,000 square feet

○ Between 10,001 and 25,000 square feet

○ Between 25,001 and 50,000 square feet

○ Between 50,001 and 100,000 square feet

○ Between 100,001 and 200,000 square feet

○ Between 200,001 and 500,000 square feet

○ More than 500,000 square feet

○ Don't know

Q9 How many different businesses or tenants occupy this building? We're looking for the number of individual businesses or organizations that rent space in the building.

○ Record number of businesses or tenants

____

○ Don't know

Skip To: Q11 If How many different businesses or tenants occupy this building? We're looking for the number of i...(Record number of businesses or tenants) Is Not Empty

Q10 How many businesses or tenants would you say occupy this building? We're looking for the number of individual businesses or organizations that rent space in the building. Are there...

○ 1 business/tenant

○ 2 to 5 businesses/tenants

○ 6 to 10 businesses/tenants

○ 11 to 20 businesses/tenants

○ 21 to 50 businesses/tenants

○ 51 to 100 businesses/tenants

○ More than 100 businesses/tenants

○ Don't know

Q11 What is the approximate square footage of the space occupied by **your** business? Note that this may be less than the total square footage of the building.

○ Record square footage ____

○ Don't know

Skip To: Q13 If What is the approximate square footage of the space occupied by your business? Note that this may...(Record square footage) Is Not Empty

Q12 Would you say that your business occupies...

○ Less than 1,000 square feet

○ Between 1,001 and 5,000 square feet

○ Between 5,001 and 10,000 square feet

○ Between 10,001 and 25,000 square feet

○ Between 25,001 and 50,000 square feet

○ Between 50,001 and 100,000 square feet

○ Between 100,001 and 200,000 square feet

○ Between 200,001 and 500,000 square feet

○ More than 500,000 square feet

○ Don't know

Q13 Has your business participated in a utility-sponsored energy efficient lighting program at this location?

○ Yes

○ No

○ Don't know

Q14 Thank you for answering our questions about your building. We are looking for businesses to participate in our field study measuring light levels in various types of spaces in Minnesota buildings. Your building qualifies for our study and we'll give you a $50 gift card for participating in our study.

More information about the field study
Our field researcher will schedule a time to visit your building, ask you a few questions about your lighting system and your perception of light levels in your space. The researcher will then walk through your building and identify multiple LED-lit spaces in which to measure light levels. For each of these spaces, the researcher will record information about the lighting characteristics. This will include measuring light levels using a handheld light meter. Every effort will be made to minimize the disruption to building occupants. We anticipate that the visit will take about 4 hours, but we would only need about 30 minutes of your time. The information from this study will help Minnesota utilities improve their lighting efficiency programs.

Would you be willing to participate in our field study?

○ Yes

○ No

Skip Out of Survey If Thank you for answering our questions about your building. We are looking for businesses to parti... = No

Q15 Thank you for agreeing to participate in our field study. Our field researcher will be in contact to schedule a time to visit your building. Please provide your building address.

○ Street address: ____

○ City ____

○ State ____

○ Zipcode ____

Q16 Please provide your contact information.

○ Name ____

○ Company Name ____

○ Email address ____

○ Phone number ____

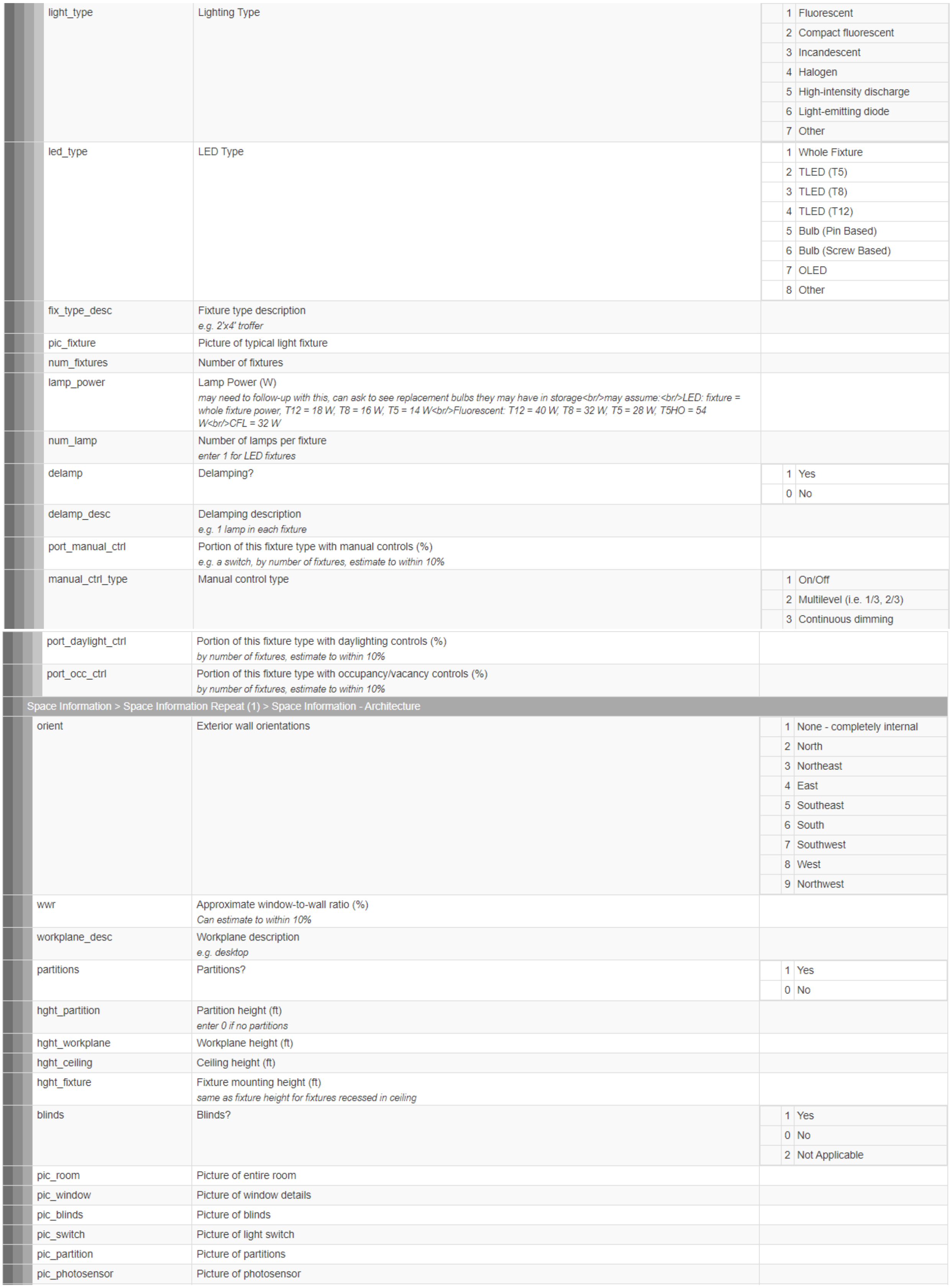
○ Job title ____

Appendix C: Site Visit Protocol

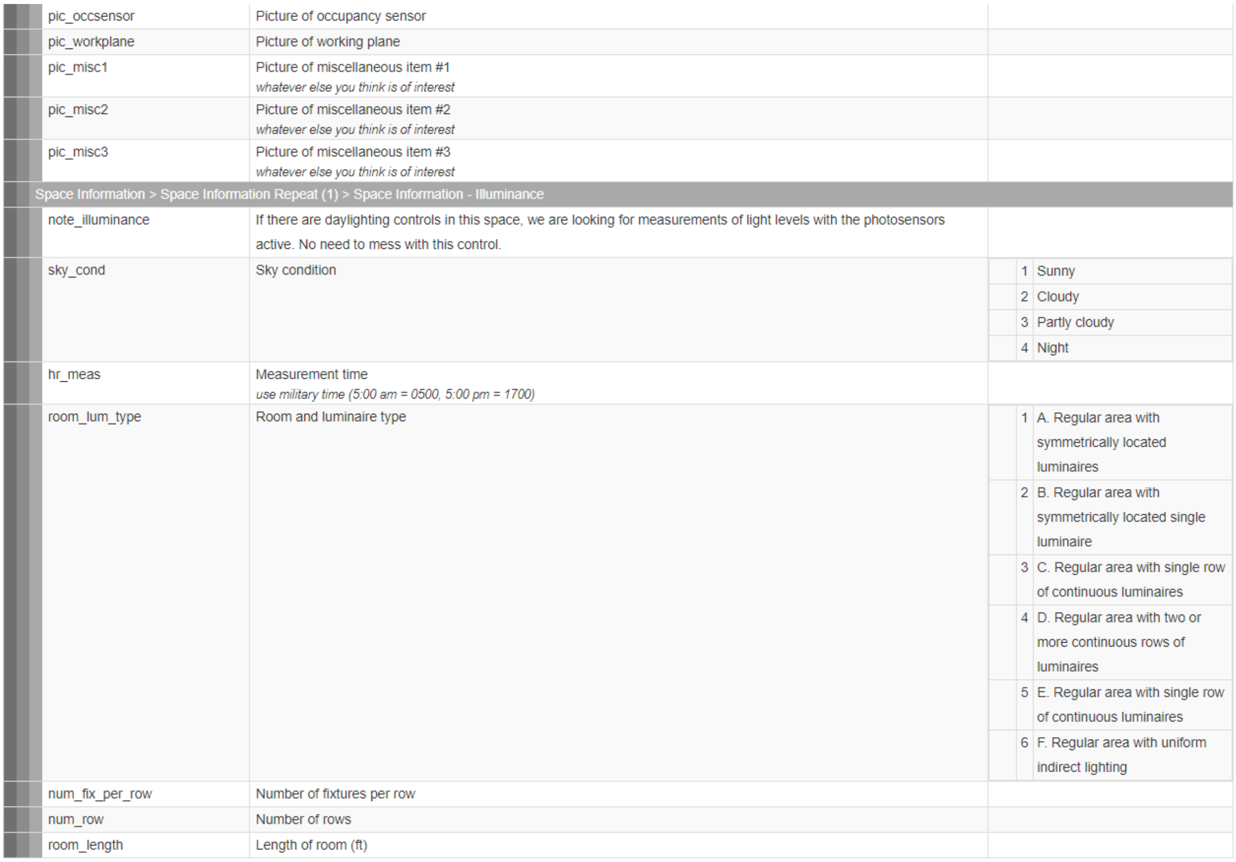
Light_Level_Site_Visit_Instrument

Field	Question	Answer
Pre Visit		
pre-visit_intro	Fill out this section in the car prior to going into the business.	
bldgid	Enter the building ID number *This will auto-populate survey data*	
researcher	Who are you?	1 Allie Cardiel 2 Mikhaila Calice 3 Leith Nye 4 Scott Schuetter 5 Jennifer Li
date_visit	Enter the date of the site visit	
bldg_pic	Take a picture of the building	
ID check		
check_id_note	If the Building ID number was typed correctly, you should see the business name and address here: [company_surv] at [address_surv] *If you don't see it, go back and double check the Business ID #. Be sure there aren't extra spaces at the end.*	
Interview		
dwelling_intro	Upon entering the business, introduce yourself and remind owner of the site visit process. Describe what you will be doing, how long it will take and ask if they have any questions. You'll start with a short interview, followed by a walk-through to familiarize you with the spaces. Next, you'll cataloguing lighting and measuring light levels in the building. You can be as autonomous during this period as they're comfortable with. You'll be taking pictures and using a tablet to collect information. You'll be turning on and off lights in various spaces, but will try to keep disruption to a minimum. Ask them if they have any questions. Mention that all information collected will be used anonymously. And that they'll get a summary of potential opportunities for improvement at the end of this. This project is funded by the Minnesota Conservation Applied Research and Development Grant program. It's goal is to characterize the light levels in commercial buildings.	
interview_light_level	In your opinion, how are light levels?	1 Too low 2 Just right 3 Too High
interview_light_level_desc	Additional detail about light levels	
occ_complaints	Have there been any occupant complaints regarding light levels?	1 Yes 0 No
occ_complaints_desc	Additional detail about occupant complaints	
maint_ctrls	Who is responsible for maintaining lighting controls?	1 Not applicable 2 Contractor 3 Owner with manufacturer 4 Owner only 5 Property Management 6 Other
maint_ctrls_other	Describe "other" responsible party for maintaining lighting controls (if applicable)	
cutsheets_manu	Would you be able to find and share the LED lighting's cut sheets or specifications?	1 Yes 0 No
fixt_manu	Fixture manufacturer:	
ctrls_manu	Controls manufacturer:	
light_year	What year was the lighting installed or retrofit?	
light_ctrls	Which of the following lighting controls apply to your businesses lighting?	1 None 2 Daylight/Photosensor (Interior only) 3 Occupancy/Vacancy 4 Timeclock 5 Task Tuning (likely have to explain)
wireless_ctrls	Are these lighting controls wireless?	1 Yes 0 No
change_of_use	Has there been a significant change of use to the spaces since the lighting was installed or retrofit?	1 Yes 0 No
change_of_use_year	What year was the change of use? (if applicable)	
change_of_use_desc	Additional detail about change of use	

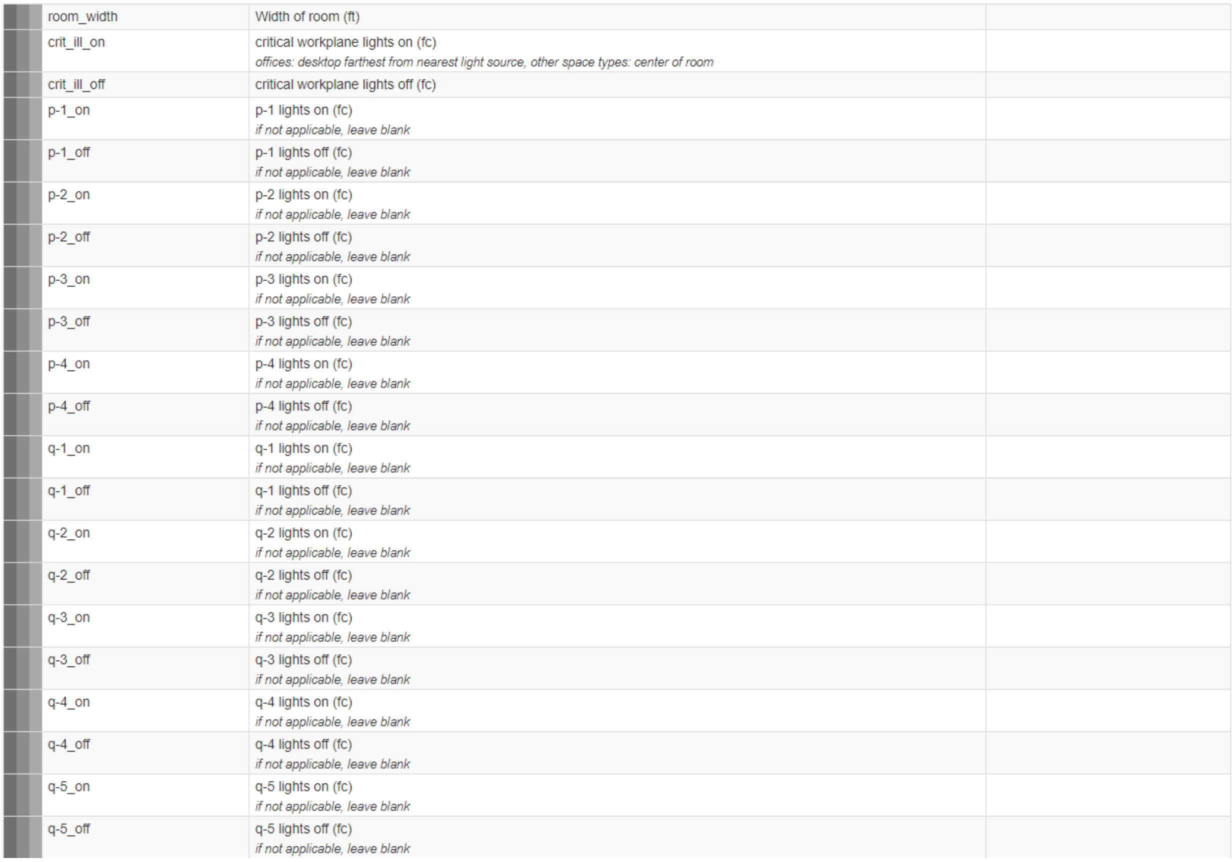
occupied_period	What are this businesses typical hours of occupancy? *not their business hours, but when someone is generally in the space*	1 Weekdays (8 hour workday); No weekend occupancy 2 Weekdays (8 hour workday); Some weekend occupancy 3 Two shifts 4 Three shifts 5 24/7 6 Other
occupied_period_other	Describe "other" occupied period (if applicable)	
occupant_survey_yesno	We'd like to have the occupants of the characterized spaces fill out a brief, online survey. The intent of this survey is to understand their level of satisfaction with the lighting system. Would you be willing to pass along a link to the survey to the occupants? *We will follow up with the link and which rooms we are interested in.*	1 Yes 0 No
occupant_survey_email	What is the best email to send the link and room information to	
note_walkthru	The interview is now complete. Ask for a brief walk thru to familiarize you with the various spaces. Mention that you'd like them to point out LED lit spaces, as well as any photosensors or occupancy sensors that they know of. After that, you can be as autonomous as they are comfortable with. You'd like to circle back at the end for a brief wrap-up.	
interview_general_notes	Optional: Add any additional notes pertaining to "Interview" section here	
Space Information		
bldg_type	Thinking about the building as a whole, what are the spaces primarily used for?	1 Manufacturing 2 Education 3 Office 4 DON'T USE Outpatient Healthcare 5 Warehouse & Storage
num_spaces	Number of spaces to characterize *Try to get at least one of each space type (2 warehouse in Warehouse and Manufacturing, 3 classrooms in Education). If time allows, more than one for a given space type if they have unique fixture types or fixture spacing.*	
Space Information > Space Information Repeat (1)		(Repeated group)
Space Information > Space Information Repeat (1) > Space Information - Operation		
space_type	Space Type	1 Open office 2 Private office 3 Conference room 4 DON'T USE Storage (not warehouse) 5 Storage (warehouse) 6 Corridor 7 Classroom
additional_photometric_data	Is this space sampled for additional photometric data?	1 Yes 0 No
add_photo_data_space_name	Space Name *Enter the same name on photometric data form, allows us to match datasets later*	
space_area	Space Area (ft^2)	
num_occupants	Number of Occupants *count chairs*	
occupant_age	Occupant Age Range	1 < 25 years old 2 25 to 65 years old 3 > 65 years old
tasks	Occupant Tasks *describe typical occupant tasks*	
Space Information > Space Information Repeat (1) > Space Information - Lighting		
num_fix_types	Number of fixture types	
Space Information > Space Information Repeat (1) > Space Information - Lighting > Fixture Type Repeat (1)		(Repeated group)
note_fix_type	Reminder that the following questions are specific to a single fixture type	
installed_type	When was this fixture type installed?	1 As part of new construction 2 As part of retrofit 3 Other



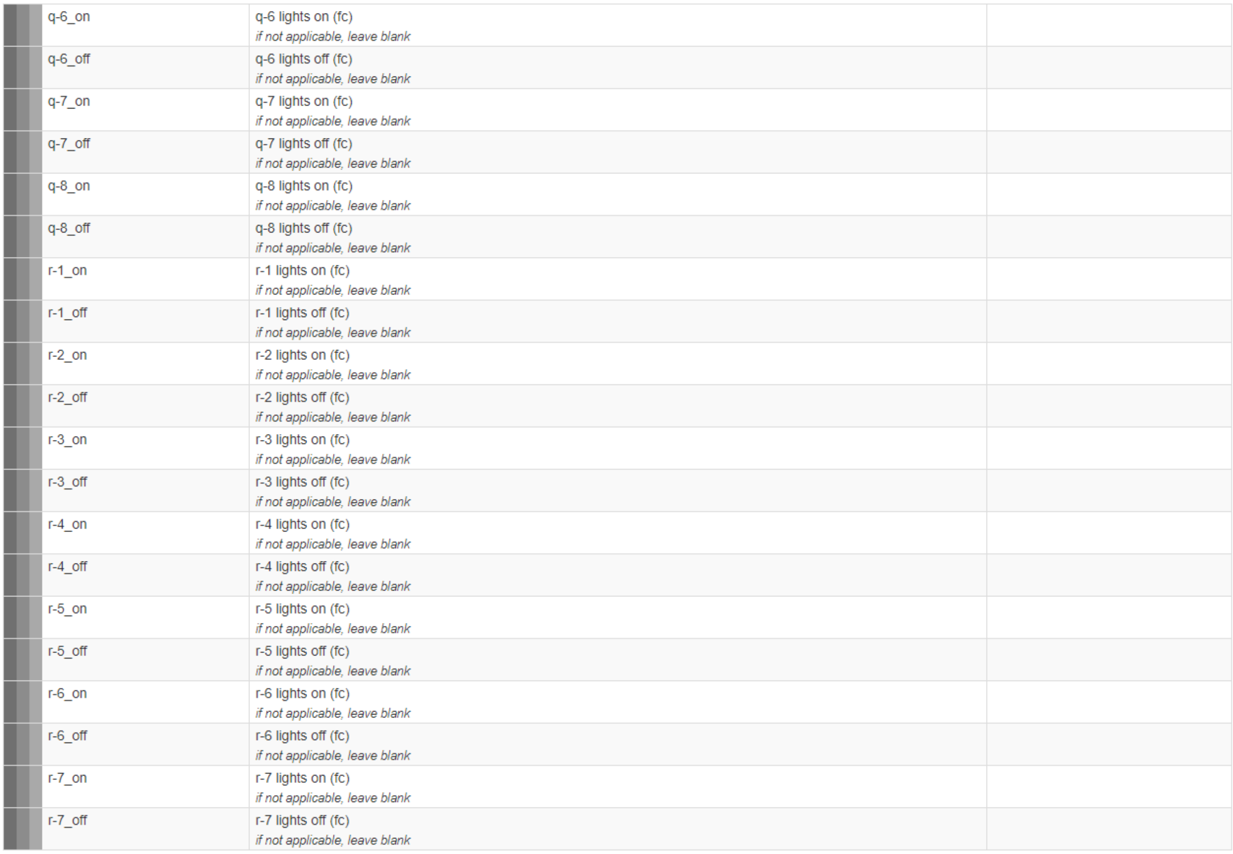
light_type	Lighting Type	1	Fluorescent
		2	Compact fluorescent
		3	Incandescent
		4	Halogen
		5	High-intensity discharge
		6	Light-emitting diode
		7	Other
led_type	LED Type	1	Whole Fixture
		2	TLED (T5)
		3	TLED (T8)
		4	TLED (T12)
		5	Bulb (Pin Based)
		6	Bulb (Screw Based)
		7	OLED
		8	Other
fix_type_desc	Fixture type description *e.g. 2'x4' troffer*		
pic_fixture	Picture of typical light fixture		
num_fixtures	Number of fixtures		
lamp_power	Lamp Power (W) *may need to follow-up with this, can ask to see replacement bulbs they may have in storage may assume: LED: fixture = whole fixture power, T12 = 18 W, T8 = 16 W, T5 = 14 W Fluorescent: T12 = 40 W, T8 = 32 W, T5 = 28 W, T5HO = 54 W CFL = 32 W*		
num_lamp	Number of lamps per fixture *enter 1 for LED fixtures*		
delamp	Delamping?	1	Yes
		0	No
delamp_desc	Delamping description *e.g. 1 lamp in each fixture*		
port_manual_ctrl	Portion of this fixture type with manual controls (%) *e.g. a switch, by number of fixtures, estimate to within 10%*		
manual_ctrl_type	Manual control type	1	On/Off
		2	Multilevel (i.e. 1/3, 2/3)
		3	Continuous dimming
port_daylight_ctrl	Portion of this fixture type with daylighting controls (%) *by number of fixtures, estimate to within 10%*		
port_occ_ctrl	Portion of this fixture type with occupancy/vacancy controls (%) *by number of fixtures, estimate to within 10%*		
Space Information > Space Information Repeat (1) > Space Information - Architecture			
orient	Exterior wall orientations	1	None - completely internal
		2	North
		3	Northeast
		4	East
		5	Southeast
		6	South
		7	Southwest
		8	West
		9	Northwest
wwr	Approximate window-to-wall ratio (%) *Can estimate to within 10%*		
workplane_desc	Workplane description *e.g. desktop*		
partitions	Partitions?	1	Yes
		0	No
hght_partition	Partition height (ft) *enter 0 if no partitions*		
hght_workplane	Workplane height (ft)		
hght_ceiling	Ceiling height (ft)		
hght_fixture	Fixture mounting height (ft) *same as fixture height for fixtures recessed in ceiling*		
blinds	Blinds?	1	Yes
		0	No
		2	Not Applicable
pic_room	Picture of entire room		
pic_window	Picture of window details		
pic_blinds	Picture of blinds		
pic_switch	Picture of light switch		
pic_partition	Picture of partitions		
pic_photosensor	Picture of photosensor		



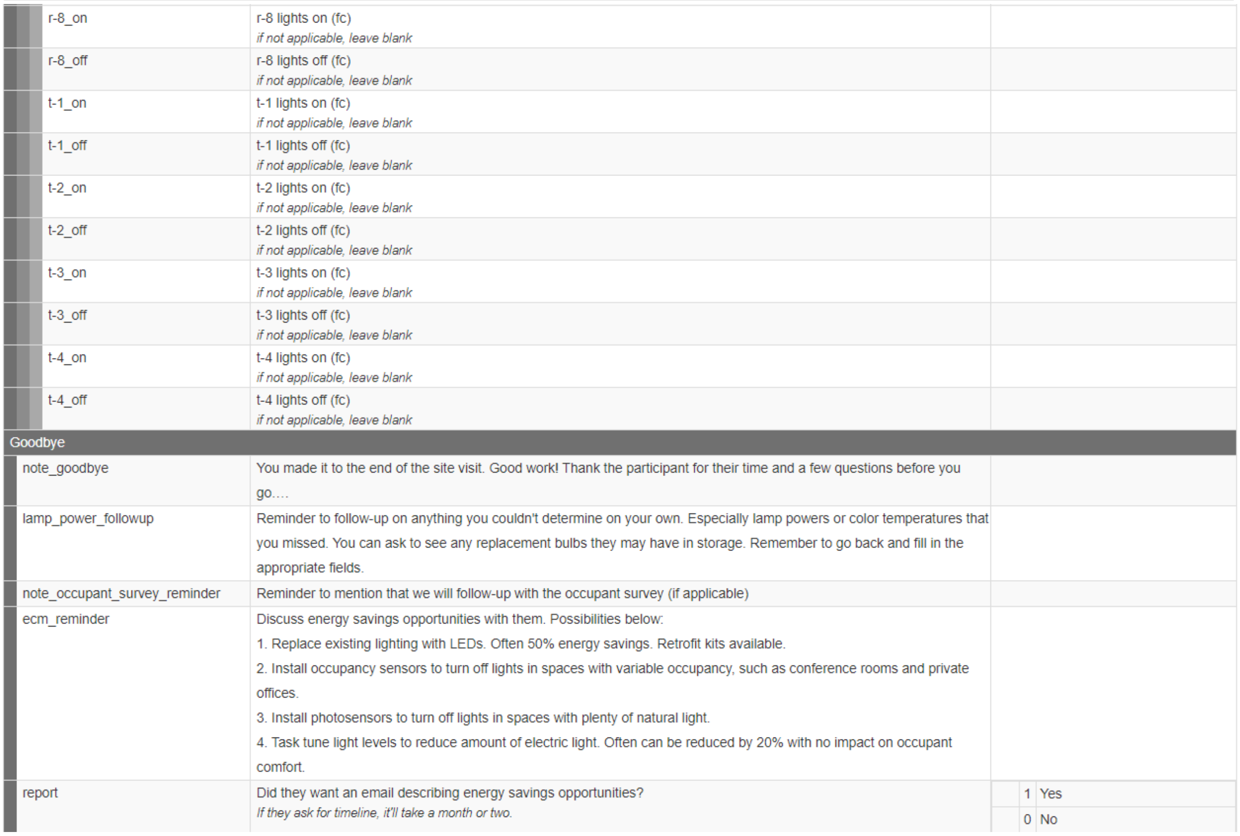
pic_occsensor	Picture of occupancy sensor	
pic_workplane	Picture of working plane	
pic_misc1	Picture of miscellaneous item #1 *whatever else you think is of interest*	
pic_misc2	Picture of miscellaneous item #2 *whatever else you think is of interest*	
pic_misc3	Picture of miscellaneous item #3 *whatever else you think is of interest*	
Space Information > Space Information Repeat (1) > Space Information - Illuminance		
note_illuminance	If there are daylighting controls in this space, we are looking for measurements of light levels with the photosensors active. No need to mess with this control.	
sky_cond	Sky condition	1 Sunny 2 Cloudy 3 Partly cloudy 4 Night
hr_meas	Measurement time *use military time (5:00 am = 0500, 5:00 pm = 1700)*	
room_lum_type	Room and luminaire type	1 A. Regular area with symmetrically located luminaires 2 B. Regular area with symmetrically located single luminaire 3 C. Regular area with single row of continuous luminaires 4 D. Regular area with two or more continuous rows of luminaires 5 E. Regular area with single row of continuous luminaires 6 F. Regular area with uniform indirect lighting
num_fix_per_row	Number of fixtures per row	
num_row	Number of rows	
room_length	Length of room (ft)	



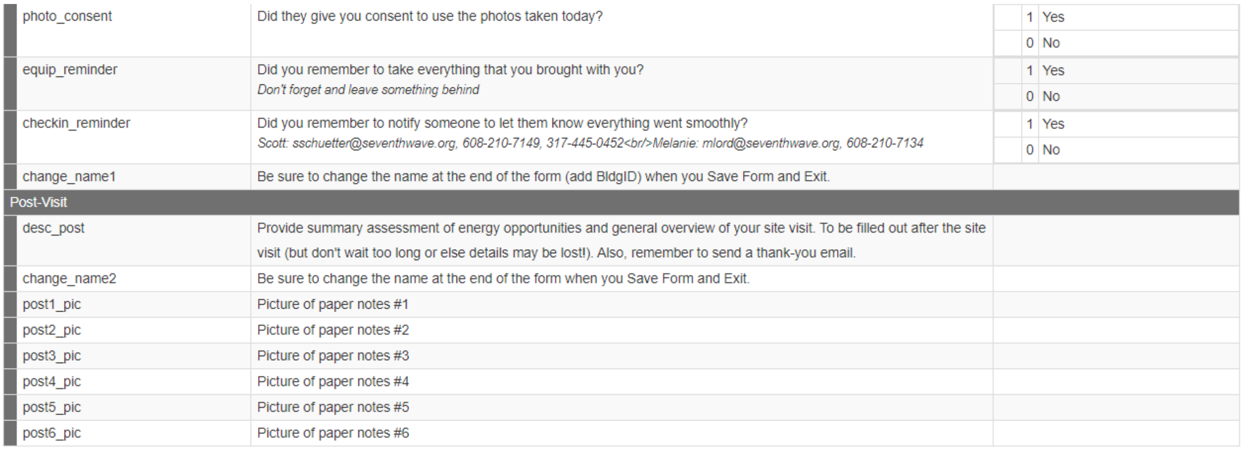
room_width	Width of room (ft)	
crit_ill_on	critical workplane lights on (fc) *offices: desktop farthest from nearest light source, other space types: center of room*	
crit_ill_off	critical workplane lights off (fc)	
p-1_on	p-1 lights on (fc) *if not applicable, leave blank*	
p-1_off	p-1 lights off (fc) *if not applicable, leave blank*	
p-2_on	p-2 lights on (fc) *if not applicable, leave blank*	
p-2_off	p-2 lights off (fc) *if not applicable, leave blank*	
p-3_on	p-3 lights on (fc) *if not applicable, leave blank*	
p-3_off	p-3 lights off (fc) *if not applicable, leave blank*	
p-4_on	p-4 lights on (fc) *if not applicable, leave blank*	
p-4_off	p-4 lights off (fc) *if not applicable, leave blank*	
q-1_on	q-1 lights on (fc) *if not applicable, leave blank*	
q-1_off	q-1 lights off (fc) *if not applicable, leave blank*	
q-2_on	q-2 lights on (fc) *if not applicable, leave blank*	
q-2_off	q-2 lights off (fc) *if not applicable, leave blank*	
q-3_on	q-3 lights on (fc) *if not applicable, leave blank*	
q-3_off	q-3 lights off (fc) *if not applicable, leave blank*	
q-4_on	q-4 lights on (fc) *if not applicable, leave blank*	
q-4_off	q-4 lights off (fc) *if not applicable, leave blank*	
q-5_on	q-5 lights on (fc) *if not applicable, leave blank*	
q-5_off	q-5 lights off (fc) *if not applicable, leave blank*	



q-6_on	q-6 lights on (fc) *if not applicable, leave blank*	
q-6_off	q-6 lights off (fc) *if not applicable, leave blank*	
q-7_on	q-7 lights on (fc) *if not applicable, leave blank*	
q-7_off	q-7 lights off (fc) *if not applicable, leave blank*	
q-8_on	q-8 lights on (fc) *if not applicable, leave blank*	
q-8_off	q-8 lights off (fc) *if not applicable, leave blank*	
r-1_on	r-1 lights on (fc) *if not applicable, leave blank*	
r-1_off	r-1 lights off (fc) *if not applicable, leave blank*	
r-2_on	r-2 lights on (fc) *if not applicable, leave blank*	
r-2_off	r-2 lights off (fc) *if not applicable, leave blank*	
r-3_on	r-3 lights on (fc) *if not applicable, leave blank*	
r-3_off	r-3 lights off (fc) *if not applicable, leave blank*	
r-4_on	r-4 lights on (fc) *if not applicable, leave blank*	
r-4_off	r-4 lights off (fc) *if not applicable, leave blank*	
r-5_on	r-5 lights on (fc) *if not applicable, leave blank*	
r-5_off	r-5 lights off (fc) *if not applicable, leave blank*	
r-6_on	r-6 lights on (fc) *if not applicable, leave blank*	
r-6_off	r-6 lights off (fc) *if not applicable, leave blank*	
r-7_on	r-7 lights on (fc) *if not applicable, leave blank*	
r-7_off	r-7 lights off (fc) *if not applicable, leave blank*	



r-8_on	r-8 lights on (fc) *if not applicable, leave blank*	
r-8_off	r-8 lights off (fc) *if not applicable, leave blank*	
t-1_on	t-1 lights on (fc) *if not applicable, leave blank*	
t-1_off	t-1 lights off (fc) *if not applicable, leave blank*	
t-2_on	t-2 lights on (fc) *if not applicable, leave blank*	
t-2_off	t-2 lights off (fc) *if not applicable, leave blank*	
t-3_on	t-3 lights on (fc) *if not applicable, leave blank*	
t-3_off	t-3 lights off (fc) *if not applicable, leave blank*	
t-4_on	t-4 lights on (fc) *if not applicable, leave blank*	
t-4_off	t-4 lights off (fc) *if not applicable, leave blank*	
Goodbye		
note_goodbye	You made it to the end of the site visit. Good work! Thank the participant for their time and a few questions before you go….	
lamp_power_followup	Reminder to follow-up on anything you couldn't determine on your own. Especially lamp powers or color temperatures that you missed. You can ask to see any replacement bulbs they may have in storage. Remember to go back and fill in the appropriate fields.	
note_occupant_survey_reminder	Reminder to mention that we will follow-up with the occupant survey (if applicable)	
ecm_reminder	Discuss energy savings opportunities with them. Possibilities below: 1. Replace existing lighting with LEDs. Often 50% energy savings. Retrofit kits available. 2. Install occupancy sensors to turn off lights in spaces with variable occupancy, such as conference rooms and private offices. 3. Install photosensors to turn off lights in spaces with plenty of natural light. 4. Task tune light levels to reduce amount of electric light. Often can be reduced by 20% with no impact on occupant comfort.	
report	Did they want an email describing energy savings opportunities? *If they ask for timeline, it'll take a month or two.*	1 Yes 0 No



photo_consent	Did they give you consent to use the photos taken today?	1 Yes 0 No
equip_reminder	Did you remember to take everything that you brought with you? *Don't forget and leave something behind*	1 Yes 0 No
checkin_reminder	Did you remember to notify someone to let them know everything went smoothly? *Scott: sschuetter@seventhwave.org, 608-210-7149, 317-445-0452 Melanie: mlord@seventhwave.org, 608-210-7134*	1 Yes 0 No
change_name1	Be sure to change the name at the end of the form (add BldgID) when you Save Form and Exit.	
Post-Visit		
desc_post	Provide summary assessment of energy opportunities and general overview of your site visit. To be filled out after the site visit (but don't wait too long or else details may be lost!). Also, remember to send a thank-you email.	
change_name2	Be sure to change the name at the end of the form when you Save Form and Exit.	
post1_pic	Picture of paper notes #1	
post2_pic	Picture of paper notes #2	
post3_pic	Picture of paper notes #3	
post4_pic	Picture of paper notes #4	
post5_pic	Picture of paper notes #5	
post6_pic	Picture of paper notes #6	

Appendix D: Occupant Survey

Q1
Slipstream is working with the Minnesota Department of Commerce to study the lighting system in your building. If you have a moment, we'd appreciate your feedback. Thank you!

This survey is completely voluntary.

Page Break

Q2 First we need some information to identify the lighting system site.

Q3 What is the name of your company:

____

Q4 Please enter the building ID provided in the email invite:

____

Page Break

Q5 Which of the following best describes your workspace?

○ Private office

○ Open office

○ Conference room

○ Storage (warehouse)

○ Storage (not warehouse)

○ Classroom

○ Other (please describe) ____

Page Break

Q6 Is your workspace within 15 feet of a window?

○ Yes

○ No

Page Break

Q7 Do you have any of the following controls over the lighting in your workspace? Select all that apply.

☐ Manual switch

☐ Manual dimmer

☐ Automated occupancy sensor which turns lights off when no one is present

☐ Automated light sensor which dims the lights when daylight is present

☐ Window blinds or shades

☐ Desk (task) lamp

☐ None of the above

☐ Other (please describe) ____

Page Break

Q8 How satisfied are you with...

	Extremely satisfied	Somewhat satisfied	Neither satisfied nor dissatisfied	Somewhat dissatisfied	Extremely dissatisfied
the amount of light in your workspace	○	○	○	○	○
your ability to control your overhead lighting	○	○	○	○	○
the visual comfort of the lighting (glare, reflections, contrast)	○	○	○	○	○

Page Break

Q9 How would you describe the effect of the quality of the overhead lighting on your ability to do your work? Does it...

○ enhance your ability to do your work

○ interfere with your ability to do your work

○ have no effect on your ability to do your work

○ other (please describe) ____

Q10 Are there any other issues related to the lighting in your workspace that are important to you? Please describe.

____

____

____

____

Appendix E: Task Tuning Checklist

Site/Space Name: _________________________________ Date:_________

Before the Visit

- ☐ Building address, contact name, cell phone number of building contact
- ☐ Obtain and review relevant building drawings (hardcopy or electronic)
- ☐ Familiarize yourself with the lighting system's controls by reviewing electronic documentation. Identify the steps necessary to adjust the system's high end trim and/or photosensor setpoint.
- ☐ Ask building contact to have lighting controls interface device available (i.e. handheld device or laptop)

During the Visit

- ☐ Identify the space or spaces to be task tuned.
- Task tuning of a space involves understanding how fixtures are controlled and which fixtures are grouped together. Generally, a zone is identified as a group of fixtures that have the same controls (i.e. an entire conference room with modifiable scenes, the portion of an open office controlled by a photosensor)
- The light levels in every single space in a building should not be measured. Instead, the light levels in a sample of representative spaces should be measured. The calculated reduction in light levels should then be applied to all similar spaces.
- ☐ Hand out pre-adjustment occupant surveys (ideally done prior to visit if possible)
- ☐ Analyze results of occupant survey. If there is a high level of dissatisfaction with the light levels in the space, consider adjusting approach accordingly. i.e. not task tuning a space, or not task tuning a particular space as aggressively.
- ☐ Fill out miscellaneous information below

Miscellaneous Information

Lighting	
Sky Condition	
Time of Day	
Space Type	
Predominant Visual Task	
Approximate Average Age of Occupants	

Measure Untuned Critical Illuminance

- “Lights Off” reading not necessary if no daylight is present (i.e. nighttime, interior space, or able to draw blinds).
- Take “Lights On” followed by “Lights Off” readings at a given location as quickly as possible as daylight (if present) may change light levels within the space.
- Allow sufficient time between locations to allow light levels to stabilize after making any control changes.
- When taking handheld readings, use tripod or hold sensor away from body to prevent shadowing on lens.
- Having more than one person is very helpful in accurately recording measurements.

☐ Select critical workplane.

- The critical workplane is the area where the predominant visual task within a space will likely be performed that also receives the least amount of light. Typically, this is a desktop away from windows and luminaires.
- Avoid task lights and direct fixture illuminance when selecting the critical workplane.

☐ Place handheld light meter at the critical workplane.

☐ Close blinds or shades if possible to minimize daylight

- If task tuning is done at night, this step is not needed.

☐ Turn on lights. Use lighting controls interface device (i.e. handheld, laptop or wall switch) to bring lights to their maximum power state. Alternately, you can cover the photosensor, if present, to trick the system into bringing the lights on to their full power. Record “Lights On” case in the table below.

☐ Turn off lights. Record “Lights Off” case in the table below.

☐ Calculate “Untuned Critical Illuminance” by taking the difference between the “Lights On” and “Lights Off” case.

Location	**“Lights On” Illuminance (fc)**	**“Lights Off” Illuminance (fc)**	**Untuned Critical Illuminance (fc)**
critical workplane			

Measure Untuned Average Illuminance

☐ Close blinds or shades if possible to minimize daylight

- If task tuning is done at night, this step is not needed.

☐ Select appropriate Room & Luminaire Type (refer to IES Lighting Handbook[10] for more detail).

☐ Record the selected Room & Luminaire Type in the table below. Make note of any orientation details.

Room & Luminaire Type	*Space to enter type*
Points Orientation Notes	*i.e. p-1 is closest to window*

☐ Hold handheld light meter at one of the locations applicable for your selected Room & Luminaire Type.

☐ Turn on lights. Use lighting controls interface device (i.e. handheld, laptop or wall switch) to bring lights to their maximum power state. Alternately, you can cover the photosensor, if present, to trick the system into bringing the lights on to their full power. Record "Lights On" case in the table below.

☐ Turn off lights. Record "Lights Off" case in the table below.

☐ Repeat process at each applicable location for your selected Room & Luminaire Type.

☐ Calculate "Untuned Electric Illuminance" by taking the difference between the "Lights On" and "Lights Off" case for each location.

Location **(i.e. q-1, q-2…)**	**"Lights On" Illuminance (fc)**	**"Lights Off" Illuminance (fc)**	**Untuned Electric Illuminance (fc)**

Location **(i.e. q-1, q-2…)**	**"Lights On" Illuminance (fc)**	**"Lights Off" Illuminance (fc)**	**Untuned Electric Illuminance (fc)**

☐ Using the appropriate equation (refer to IES Lighting Handbook[10] for more detail or Expedited Assessment section for quicker approach), calculate the Untuned Average Illuminance. When performing this calculation, use the Untuned Electric Illuminance column.

Untuned Average Illuminance (fc)	

Calculate Tuned Critical Illuminance

☐ Refer to IES Lighting Handbook[10] to determine IES Target Illuninance based on space type, predominant visual task occurring in the space and average age of space occupants and record in the table below.

☐ Calculate Tuned Critical Illuminance using the following formula and enter it in the table below.

$$Tuned\ Critical\ Illuminance = Untuned\ Critical\ Illuminance\left(\frac{IES\ Target\ Illuminance}{Untuned\ Average\ Illuminance}\right)$$

☐ Calculate Percent Reduction using the following formula and enter it in the table below.

$$Percent\ Reduction = \frac{Untuned\ Critical\ Illuminance - Tuned\ Critical\ Illuminance}{Untuned\ Critical\ Illuminance}$$

Name	**Value**
IES Target Illuminance	
Tuned Critical Illuminance	
Percent Reduction	

Implement Task Tuning

☐ Select specific task tuning scenario that is most appropriate for your space.

- A: Spaces without daylight
- B: Spaces with daylight, blinds and photosensor
- C: Spaces with daylight, blinds and no photosensor
- D: Spaces with daylight, no blinds and photosensor
- E: Spaces with daylight, no blinds and no photosensor

☐ Review and become familiar with the steps of the selected task tuning scenario outlined below.

☐ Record initial lighting control settings below.

Lighting	
Lighting Controls Information	*URL:* *Username:* *Password:* *Initial Settings:*

☐ Place handheld light meter at the critical workplane.

☐ Follow the steps of the applicable task tuning scenario below.

A: Spaces without daylight

- This scenario is the most straightforward, as it is not complicated by daylight or photosensor control.

☐ Adjust the high end trim until the measured illuminance at the critical workplane matches the Tuned Critical Illuminance.

☐ Optional: Ask occupant to perform applicable visual task (i.e. reading small print or computer screen). Ask if light levels cause any visual discomfort.

  - If No, consider decreasing light levels another 5 fc (confirmed by light meter). Only if occupant surveys show a high satisfaction with light levels and facility manager has high level of ownership with space (i.e. can quickly respond to future occupant complaints). Record updated Tuned Critical Illuminance below.
  - If Yes, increase light levels in 5 fc increments (confirmed by light meter) until occupant no longer experiences visual discomfort. Record updated Tuned Critical Illuminance below

☐ Record final lighting control settings below.

Updated Tuned Critical Illuminance (if applicable)	
Final Lighting Controls Settings (if applicable)	

<u>B: Spaces with daylight, blinds and photosensor</u>

- This scenario is more complex. However, you are able confirm that the space has been tuned appropriately as you can reduce the available daylight sufficiently.

☐ Close any blinds, thereby significantly decreasing the amount of daylight.

☐ Adjust the photosensor setpoint until the measured illuminance at the critical workplane matches the Tuned Critical Illuminance.

☐ Optional: Ask occupant to perform applicable visual task (i.e. reading small print or computer screen). Ask if light levels cause any visual discomfort.

  - If No, consider decreasing light levels another 5 fc (confirmed by light meter). Only if occupant surveys show a high satisfaction with light levels and facility manager has high level of ownership with space (i.e. can quickly respond to future occupant complaints). Record updated Tuned Critical Illuminance below.
  - If Yes, increase light levels in 5 fc increments (confirmed by light meter) until occupant no longer experiences visual discomfort. Record updated Tuned Critical Illuminance below.

☐ If lighting controls require separate high end trim adjustment, in addition to photosensor setpoint adjustment.

  - Verify blinds are closed.

  - ○ Turn off lights.
  - ○ Measure the illuminance at critical workplane. This value defines the Ambient Natural Illuminance. Record below.
  - ○ Calculate the Total Critical Illuminance below. The Total Critical Illuminance is the sum of the Ambient Natural Illuminance and the Tuned Critical Illuminance.

Tuned Critical Illuminance	+	**Ambient Natural Illuminance**	=	**Total Critical Illuminance**
	+		=	

  - ○ Turn on lights
  - ○ Adjust the high end trim until the measured illuminance at the critical workplane matches the Total Critical Illuminance.
  - ○ In order to confirm that this adjustment did not affect your photosensor setpoint adjustment, exit controls programming mode. Confirm that light meter still matches Tuned Critical Illuminance

☐ Open blinds.

☐ Record final lighting control settings below.

Updated Tuned Critical Illuminance (if applicable)	
Final Lighting Controls Settings (if applicable)	

C: Spaces with daylight, blinds and no photosensor

- This scenario is more complex. However, you are able confirm that the space has been tuned appropriately as you can reduce the available daylight sufficiently.

☐ Close any blinds, thereby significantly decreasing the amount of daylight.

☐ Turn off lights.

☐ Measure the illuminance at the critical workplane. This defines the Ambient Natural Illuminance. Record below.

☐ Calculate the Total Critical Illuminance below. The Total Critical Illuminance is the sum of the Ambient Natural Illuminance and the Tuned Critical Illuminance.

Tuned Critical Illuminance	+	**Ambient Natural Illuminance**	=	**Total Critical Illuminance**
	+		=	

☐ Turn on lights

☐ Adjust the high end trim until the measured illuminance at the critical workplane matches the Total Critical Illuminance.

☐ Optional: Ask occupant to perform applicable visual task (i.e. reading small print or computer screen). Ask if light levels cause any visual discomfort.

  ○ If No, consider decreasing light levels another 5 fc (confirmed by light meter). Only if occupant surveys show a high satisfaction with light levels and facility manager has high level of ownership with space (i.e. can quickly respond to future occupant complaints). Record updated Tuned Critical Illuminance below.

  ○ If Yes, increase light levels in 5 fc increments (confirmed by light meter) until occupant no longer experiences visual discomfort. Record updated Tuned Critical Illuminance below.

☐ Open blinds.

☐ Record final lighting control settings below.

Updated Tuned Critical Illuminance (if applicable)	
Final Lighting Controls Settings (if applicable)	

<u>D: Spaces with daylight, no blinds and photosenor</u>

- In this scenario, you are unable to confirm that the space has been tuned appropriately as you cannot reduce the available daylight sufficiently. Also, you cannot confirm that the tuned light levels do not cause visual discomfort. Consider revisiting this space at night if possible.

☐ Access lighting control system and find Untuned Photosensor Setpoint. Record below.

☐ Calculated Tuned Photosensor Setpoint. Record below.

$$Tuned\ Photosensor\ Setpoint = Untuned\ Photosensor\ Setpoint * Percent\ Reduction$$

Name	**Value**
Untuned Photosensor Setpoint	
Tuned Photosensor Setpoint	

☐ In lighting control system, adjust photosensor setpoint to be equal to calculated Tuned Photosensor Setpoint.

☐ If lighting controls require separate high end trim adjustment, in addition to photosensor setpoint adjustment, access lighting control system and find Untuned High End Trim. Record below.

☐ Calculate Tuned High End Trim. Record below.

$$Tuned\ High\ End\ Trim = Untuned\ High\ End\ Trim * Percent\ Reduction$$

Name	**Value**
Untuned High End Trim	
Tuned High End Trim	

☐ In lighting control system, adjust high end trim to be equal to calculated Tuned High End Trim.

☐ Record final lighting control settings below.

Final Lighting Controls Settings (if applicable)	

<u>E: Spaces with daylight, no blinds and no photosenor</u>

- In this scenario, you are unable to confirm that the space has been tuned appropriately as you cannot reduce the available daylight sufficiently. Also, you cannot confirm that the tuned light levels do not cause visual discomfort. Consider revisiting this space at night if possible.

☐ Turn off lights.

☐ Measure the illuminance at the critical workplane. This defines the Ambient Natural Illuminance. Record below.

☐ Calculate the Total Critical Illuminance below. The Total Critical Illuminance is the sum of the Ambient Natural Illuminance and the Tuned Critical Illuminance.

Tuned Critical Illuminance	+	**Ambient Natural Illuminance**	=	**Total Critical Illuminance**
	+		=	

☐ Turn on lights

☐ Adjust the high end trim until the measured illuminance at the critical workplane matches the Total Critical Illuminance.

☐ Record final lighting control settings below.

Final Lighting Controls Settings (if applicable)	

After the Visit

☐ Ask facility manager to re-administer occupant surveys several weeks after task tuning was completed.

☐ Compile results of occupant survey.

☐ If surveys show high levels of occupant discomfort, consider retuning space with higher target illuminance levels.

Appendix F: Critical Workplane Illuminance

A method for determining suitable critical workplane illuminance without occupant feedback involves the following. Note that this method deviates from the method we outline in Appendix E, Task Tuning Checklist, by tuning based on critical illuminance and not average illuminance:

1. Based on IES recommendations, determine the tuned average illuminance for the space

2. The ratio between the average and critical illuminance is defined as:

$$U_{ave/min} = \frac{Tuned\ Average\ Illuminance}{Tuned\ Critical\ Illuminance}$$

The IES *Lighting Handbook* recommends that this ratio be below 1.5.[10] For example, a space with an average illuminance of 30 fc should not have any workplane illuminance below 20 fc.

3. Given the recommended ratio between average and critical illuminance, calculate a tuned critical illuminance for the space.

$$tuned\ critical\ illuminance = \frac{tuned\ average\ illuminance}{1.5}$$

4. Perform task tuning on the space, such that the illuminance measured at the critical workplane by a light meter is equivalent to the calculated tuned critical illuminance above.

Within this method, the space's actual average illuminance is not required. In fact, for problematic spaces with high averaged-to-tuned illuminance ratios ($U_{ave/min}$ >1.5), the average illuminance after tuning will be much higher than that recommended by IES. However, the point of this approach is not to have the correct average illuminance, but rather to have a reasonable minimum illuminance.

As noted in Appendix E, Task Tuning Checklist, there are five types of spaces that could be tuned:

A: Spaces without daylight

B: Spaces with daylight, blinds and photosensor

C: Spaces with daylight, blinds and no photosensor

D: Spaces with daylight, no blinds and photosensor

E: Spaces with daylight, no blinds and no photosensor

The differentiating features between each is whether the space has daylight present, whether you can reduce the amount of daylight by adjusting blinds, and whether the lights are controlled by a photosensor. Spaces without daylight are the simplest to tune since there is no daylight to contend with or photosensor controls to adjust. These spaces may be tuned at any time. Having blinds in spaces with daylight allows the person tuning the system to reduce the available daylight to below the recommended average illuminance. Without blinds, the available daylight can be significantly higher than the recommended average illuminance, resulting in an inability to check through light meter measurements that the photosensor setpoint and high end trim are properly adjusted. Additionally, if the amount of daylight is too high, then occupants will not be able to give their feedback as to whether or not the light levels after tuning are appropriate. Ideally, tuning in spaces without blinds should be done during periods of low daylight such as under cloudy sky conditions.